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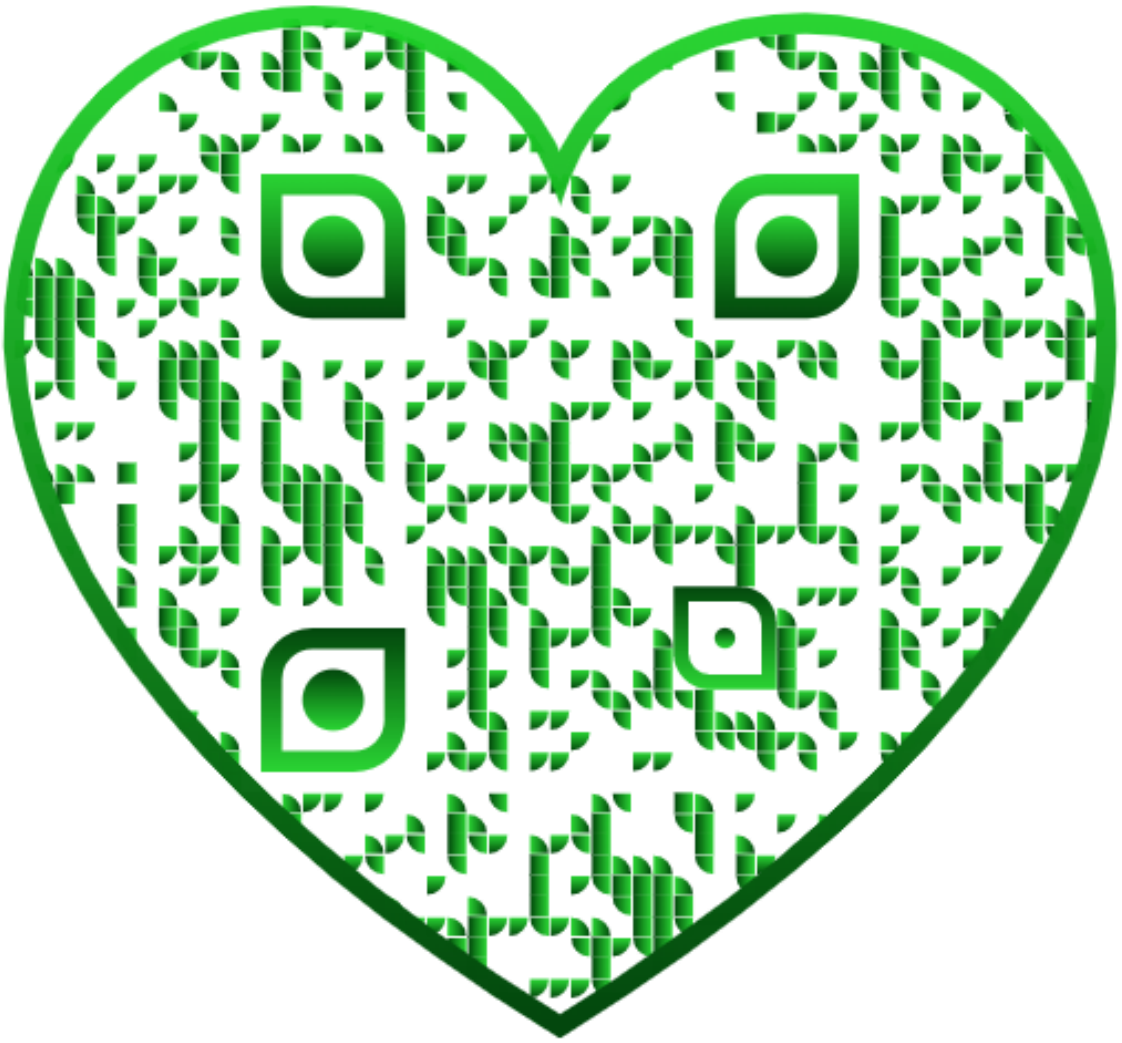

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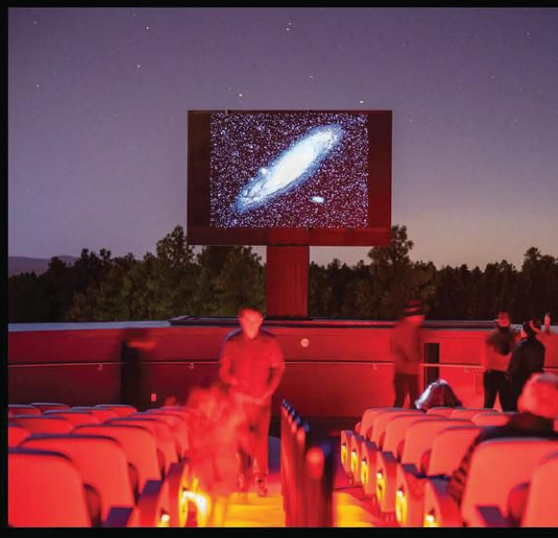

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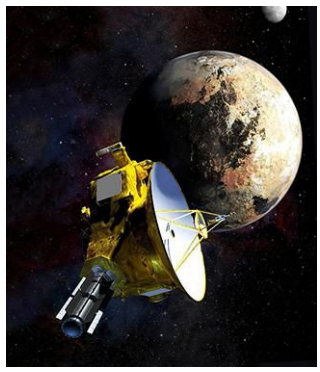

ON THE COVER

When the New Horizons mission flew past the Pluto system in 2015, as imagined here, it revolutionized our understanding of the distant dwarf planet and many other Kuiper Belt objects. JHUAPL/SWRI

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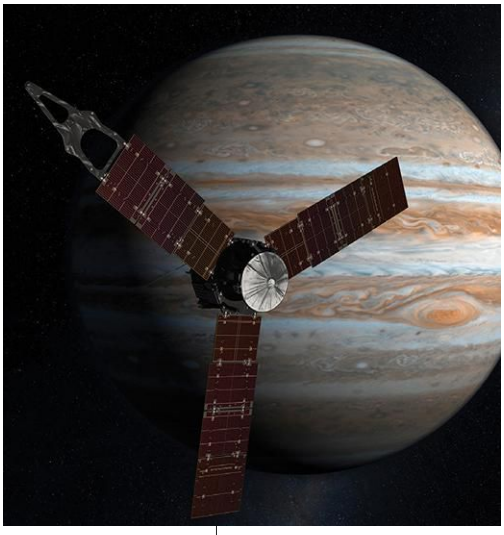
A revolutionary story



PI-led missions like the Juno spacecraft to Jupiter represent a revolution in planetary science.
NASA/JPL

One of my old pals in the world of astronomy, S. Alan Stern, has written a great story that we feature in this issue. You undoubtedly know Alan too — or know of him — as he is among other things the leader of the New Horizons mission that flew past Pluto and then out into deeper space. Alan's contribution this month, "5 modern revolutions in planetary science" (page 12), is a story I hope will strike you as particularly important.

During Alan's 40-year career, the field of planetary science has changed dramatically. At least five revolutions have transformed our thirst for knowledge about planetary science and the solar system. The story provides a guided tour through those pivotal moments that have created the picture of our nearest surroundings in the galaxy so vividly in our minds.

The first such game-changing moment arrived early in the 19th century when scientists discovered the first minor planet, 1 Ceres. This opened a window to the complexity of the solar system as containing, as Alan puts it, "a whole zoo of such worlds."

Other momentous realizations arrived as well. These more modern revolutions have shaped what we now know. The discovery of the Kuiper Belt in the 1990s changed our view of things completely. The discovery of exoplanets around the same time also opened our view of the commonality of worlds. The discovery of ocean worlds made it clear that huge numbers of planets exist that could easily harbor life.

And how planetary science is done has also dramatically changed: The rise of PI-led missions and the explosion of commercial spaceflight have propelled us into a new era.

I hope you'll enjoy this special story, and hope it will spawn some thinking about all that's out there that we still have to discover.

Yours truly,

David J. Eicher
Editor-in-Chief

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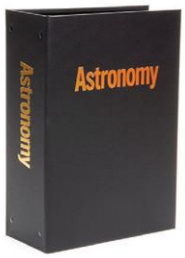

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Satellite images such as this photo of the Bahamas are a way to gauge sea level rise across the globe. NASA

We welcome your comments via email to **letters@astronomy.com**. *Please include your name, city, state, and country. Letters may be edited for space and clarity.*

For the love of science

Thank you for your bravery in dedicating the April 2025 issue to the science of climate change. In troubling times like these, it is vital for enthusiasts of all branches of science to support one another. I'm confident that the knowledge these articles provided more than makes up for the short-sighted anger that a small but vocal group of readers may be sharing. **—Alex Harkaway,** Portland, OR

Study of the stars

I very much enjoyed your article "10 women who changed astronomy" (May 2025). I recognized some of the names of the women in your article from an excellent book I read called *The Glass Universe: How the Ladies of the Harvard Observatory Took the Measure of the Stars* by Dava Sobel (Viking, 2016). A large part of the book is about Edward Pickering and his "girls" and the Harvard Observatory. So much of the foundation of astronomy (astrophotography, spectroscopy, etc.) was originated by these ladies. The book details their lives; for anyone who enjoyed your article, it's a must read. **—Joe Berry,** Moreshet, Israel

All the lights

For years, like most *Astronomy* readers, I have watched with interest the debate on how alien life might be first discovered ("Can we detect alien artifacts?", May 2025). I've often thought if alien worlds are anything like Earth, and their inhabitants are intelligent, *and* we ever obtain images of exoplanets with enough resolution to see them directly, maybe their planet would light up — like Earth does at night. From a distance, our cities are stunningly beautiful at night, shining with artificial lighting (although at the same time, it destroys our dark skies and ability to observe). A planet awash in artificial lights would certainly tell us whether we should bother to look further. **—Jay Crutchfield,** Fort Worth, TX

Erratum: *In the May story "10 women who changed astronomy," we reference three Nobel laureates under Andrea Ghez's profile, including Richard Penrose. However, this revered mathematician's name is actually Roger Penrose.*

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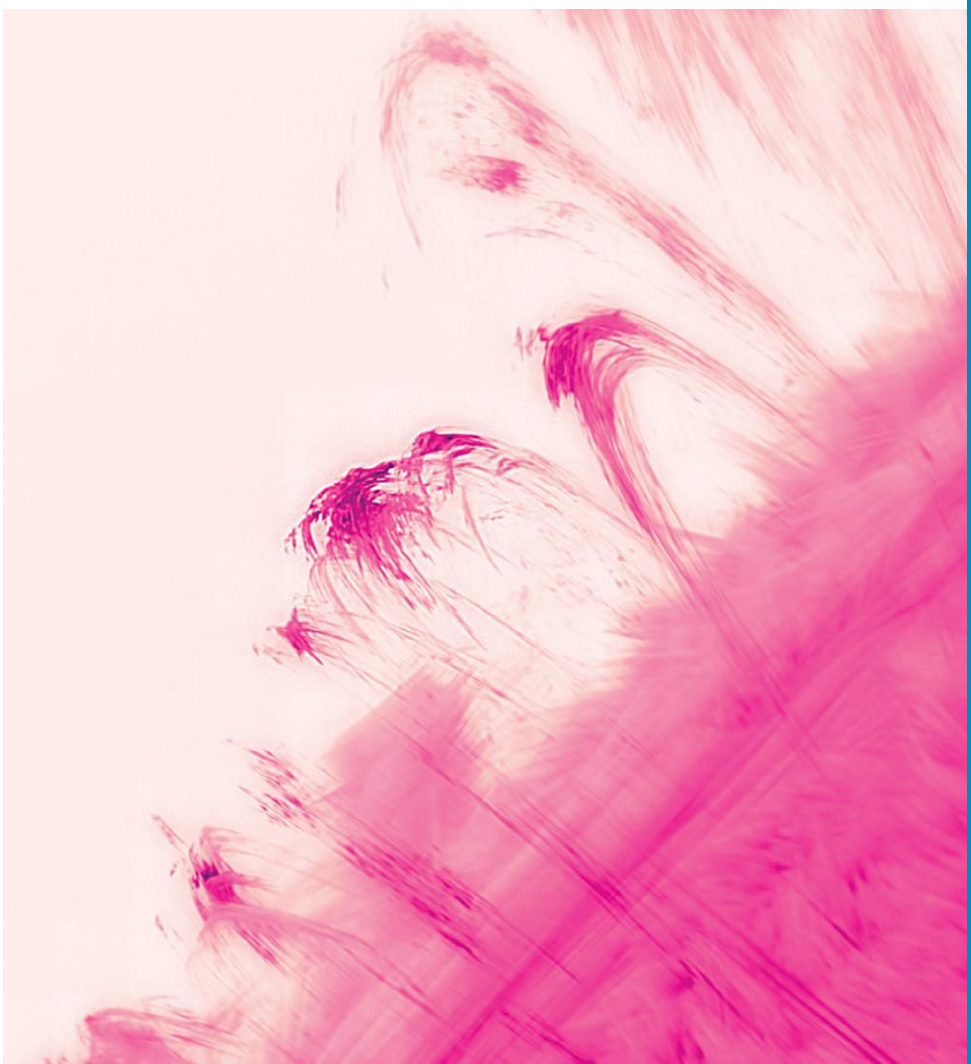
SNAPSHOT

SOLAR RAIN

Optical upgrades have yielded the sharpest ever images of the Sun's corona.



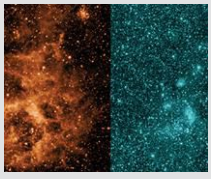
The mesmerizing dynamics of the Sun's outer atmosphere come alive in this Hydrogen-alpha view. The delicate plasma filaments — some as narrow as 12 miles (20 kilometers), say researchers — form similarly to rain on Earth: Hot plasma condenses and descends back to the Sun's surface. But, as charged particles, these droplets don't fall straight down; instead, they trace out graceful arcs along the Sun's magnetic field lines.

This unprecedented clarity is thanks to a new adaptive optics system, which corrects for image distortions caused by turbulence in Earth's atmosphere, installed at the 1.6-meter Goode Solar Telescope (GST) at Big Bear Solar Observatory in California and developed by the National Solar Observatory and the New Jersey Institute of Technology. Previously, such technology enabled sharp images of the Sun's surface, but the system at the GST is the first capable of imaging the Sun's corona.

— MARK ZASTROW

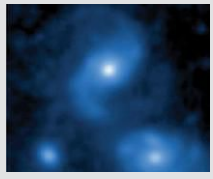
SCHMIDT ET AL./NJIT/NSO/AURA/NSF. BOTTOM FROM LEFT: NASA/JPL-CALTECH; NASA, ESA, CSA, JONATHAN NICHOLS (UNIVERSITY OF LEICESTER); MAHDI ZAMANI (ESA/WEBB); NASA, ALMA(ESO/NAOJ/NRAO); HUANG ET AL.

HOT BYTES



PUFF OF SMOKE
In some of its first images, NASA's SPHEREx mission captured a cloud of smoky molecules at mid-infrared wavelengths (left), revealing details invisible in the near infrared (right). The shots showcase the craft's unique ability to survey the entire sky in over 100 infrared bands.

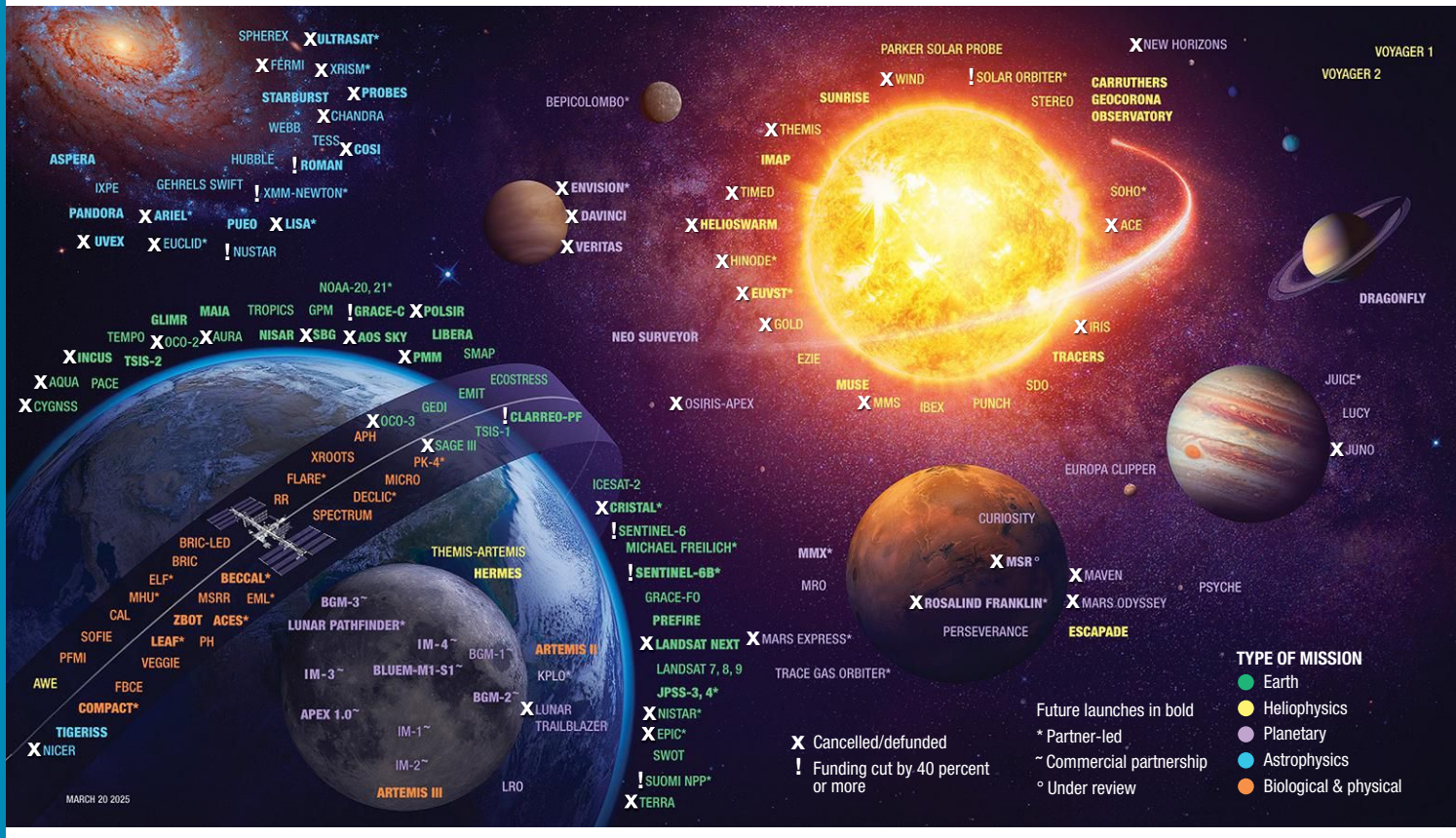
DYNAMIC DISPLAY
Jupiter's aurorae can "fizz" and "pop" with rapid, dramatic changes in brightness that vary by the second — far faster than expected — observations from the James Webb Space Telescope (JWST) reveal.



BAR EXAM
A galaxy seen just 2.6 billion years after the Big Bang has a distinct bar structure in observations from JWST (shown) and the ALMA radio telescope, suggesting such features may have evolved earlier in the life of the universe than astronomers thought.

LEADERLESS NASA FACES MASSIVE PROPOSED SCIENCE CUTS

The agency is facing an unprecedented budget crisis, with no candidate for administrator currently nominated.



FORCED RETIREMENT. NASA missions slated for cancelation or defunding are marked in this graphic with an X, while exclamation points (!) highlight those facing cuts of 40 percent or more.
NASA/*ASTRONOMY*: BROOKS MENDENHALL

The Trump administration's proposed NASA budget for 2026 calling for a 24 percent cut to the agency's funding — including a 47 percent cut to its science directorate — has sent shock waves through the astronomical and space science communities. If enacted, the budget would reduce NASA's funding from $24.8 billion to $18.8 billion — marking the agency's smallest budget since 1961 when adjusted for inflation.

NASA's Science Mission Directorate would bear the brunt of the decrease. The astrophysics division would be cut from about $1.53 billion to $523 million, a two-thirds reduction. Earth sciences would be cut by more than half to $1.036 billion, while solar science would see a similar reduction, from $805 million to $433 million. Planetary sciences would receive a 30 percent cut to $1,891.3 billion. In contrast, NASA's human exploration efforts would get an 8 percent boost.

The proposed budget, released in detail on May 30, would defund or cancel more than 40 active and future missions, roughly a third of NASA's science fleet. Among those at risk are New Horizons, continuing its journey through the Kuiper Belt; Juno, investigating Jupiter's structure and magnetic field; Mars Odyssey and MAVEN, orbiters studying Mars' atmosphere and geology; and the Chandra X-ray Observatory, which has provided the sharpest ever views of the high-energy universe since 1999. Also on the chopping block would be the upcoming Mars Sample Return, aimed at returning martian soil samples to Earth.

LEADERSHIP VACUUM

NASA's budget turmoil comes as

the agency finds itself without duly appointed leadership. On May 31, President Donald Trump unexpectedly withdrew his nomination of entrepreneur and private astronaut Jared Isaacman for NASA administrator, just days before the Senate was scheduled to vote on his confirmation. A Senate committee had advanced his nomination with bipartisan support in a 19–9 vote. As of publication, Trump had not announced a new nominee.

Isaacman had flown on two private spaceflights he purchased from SpaceX, and Elon Musk — the company's CEO and a close advisor to Trump early in his term — had advocated for his selection. Isaacman had enjoyed broad support from the commercial aerospace industry, which viewed him as a dynamic and capable leader. However, as Musk's relationship with Trump and other White House officials deteriorated in the weeks leading up to his own scheduled departure from government service, internal divisions surfaced.

According to *Bloomberg*, Sergio Gor, head of the White House Presidential Personnel Office, clashed with Musk and moved to remove Isaacman when Musk left the administration at the end of May. At a June 6 briefing, Trump said he had nominated Isaacman on Musk's recommendation, but that given Isaacman's previous political donations to Democrats, he "didn't think it was appropriate. … Look, we won. We get certain privileges, and one of the privileges is we don't have to appoint a Democrat." Isaacman has described himself as a moderate, but right-leaning.

Isaacman had shown hints of disagreement with the science cuts in the president's budget request. In written responses to questions from senators, Isaacman said that "a ~50 percent reduction to NASA's science budget does not appear to be an optimal outcome," and said he would "advocate for strong investment in space science … and for securing as much funding as the government can reasonably allocate." And in 2024, before his nomination for NASA administrator, he wrote a letter opposing plans to shut down Chandra, warning of a "death spiral for X-ray astronomy in the United States."

WITHDRAWAL SYMPTOMS. Jared Isaacman testified April 9 at a Senate confirmation hearing, where he enjoyed bipartisan support, nearly two months before his nomination was withdrawn.
U.S. SENATE COMMITTEE ON COMMERCE, SCIENCE, & TRANSPORTATION

SCIENTIFIC COMMUNITY RESPONDS

The Planetary Society warned the proposed budget cuts would deliver "an extinction-level event" to NASA's science efforts, potentially ending American leadership in space exploration and research. And the American Astronomical Society (AAS) said in a statement that it was "gravely concerned" about the proposed cuts — including similar cuts to the National Science Foundation and a smaller cut to the Department of Energy — warning they would be "catastrophic."

"These cuts would damage a broad range of research areas that will not be supported by the private sector," the AAS stated. "Without robust and sustained federal funding, the United States will lose at least a generation of talent to other countries that are increasing their investments in facilities and workforce development."

The White House budget is far from final, as Congress — where NASA often enjoys bipartisan support — ultimately controls appropriations. The Planetary Society has called the Trump White House budget "dead on arrival." And back in March, multiple U.S. senators — including Maria Cantwell (D-Wash.) and Ted Cruz (R-Texas) — introduced a NASA authorization bill that set NASA's budget at $25.5 billion. But astronomer Adam Burgasser of the University of California, San Diego, tells *Astronomy* that political support for NASA "doesn't necessarily mean supporting NASA science. It means supporting maybe NASA astronautics, but not necessarily astronomy." – JACK DALEO, SAMANTHA HILL, BROOKS MENDENHALL, M.Z.

QUICK TAKES

VESTA UNVEILED

A reanalysis of archival data from NASA's Dawn mission reveals that asteroid 4 Vesta has a uniform interior, lacking a distinct core. The finding, published April 23, challenges the view of Vesta as a layered protoplanet and raises the possibility it formed in a collision of larger bodies.

FIERY DEMISE

Cosmos 482, a Soviet Venus lander stranded in Earth orbit since 1972, reentered the atmosphere May 10 and crashed into the Indian Ocean.

PREHISTORIC BLAST

A solar storm in 12,350 B.C.E. during the last Ice Age is now the most powerful on record, researchers reported April 28. According to tree-ring radiocarbon data and a new climate-chemistry model, the event was 500 times stronger than the strongest storm of the satellite era, in 2005.

SNAKE-BIT ROVER

NASA has opted not to use any of the proposals it solicited from potential partners to take over the agency's VIPER lunar rover, whose mission was cancelled due to budget constraints. In a May 7 statement, NASA said it would announce a new strategy for VIPER in the future.

BEYOND CLOUD COMPUTING

In a bid to move data centers into space, China launched the first 12 satellites of a planned 2,800-satellite constellation from Jiuquan Satellite Launch Center on May 14. The satellites focus on AI and data processing, not communications or remote sensing.

MERGER? MAYBE

The long-predicted collision between the Milky Way Galaxy and Andromeda Galaxy (M31) is far from certain. Simulations published June 2 with updated data and the effects of the Triangulum Galaxy (M33) and the Large Magellanic Cloud reduce the merger probability to just over 50 percent. – M.Z.

HYCEAN HYPOTHESIS. A hycean world — a proposed class of exoplanet with a hydrogen-rich atmosphere and a global water ocean — orbits a red dwarf star in this artist's concept. A. SMITH, N. MADHUSUDHAN (UNIVERSITY OF CAMBRIDGE)

K2-18 b biosignature claim draws scrutiny

IN A WAVE OF NEWS STORIES and a press release published April 16, scientists announced new observations from NASA's JWST that they said strengthen the case that the exoplanet K2-18 b has molecules in its atmosphere that, on Earth, are produced only by life.

But the study, published the next day in *The Astrophysical Journal Letters*, drew strong skepticism as many astronomers questioned the claims and the statistical analysis upon which they rest. "When it comes to K2-18 b, enthusiasm is outpacing evidence," says MIT's Sara Seager, an exoplanet researcher who was not involved in the study.

The team said they are not claiming to have discovered life, and that it is vital to collect more data to confirm the detection. However, lead author Nikku Madhusudhan, an astronomer at the University of Cambridge, argued in an April 17 lecture that "currently, there is no way to explain DMS [dimethyl sulfide, one of the molecules detected] at the levels we are seeing without life." But, he added, "we are open to alternate hypotheses."

In 2023, the same team published observations from JWST that they said yielded weak hints of DMS on K2-18 b. Their recent work builds on those observations. The researchers have proposed that the planet, which they've dubbed a hycean world, could be covered with a hydrogen-rich atmosphere and a global liquid ocean.

In the new study, the authors say spectra taken with a different JWST instrument show more evidence of DMS, as well as signs of a related molecule, dimethyl disulfide (DMDS). They claim a statistical significance of 3-sigma — short of the scientific gold standard for detection of 5-sigma, but still implying there is 99.7 percent chance the signal is real.

However, a reanalysis of the data performed by Jake Taylor of the University of Oxford and submitted to the *arXiv* preprint server April 22 found little evidence for any molecular signals in the data.

And another study submitted to the *arXiv* April 30, led by Luis Welbanks of Arizona State University and Matthew Nixon of the University of Maryland, questioned the team's approach. Madhusudhan and his colleagues, they argue, had not "detected" a molecule to any level of significance: They had compared one model spectrum — an atmosphere with carbon dioxide and methane — to another model with DMS and DMDS added, without considering the possible presence of other molecules, including water vapor. Welbanks likened it to an analysis seeking to determine whether the Moon was made of sponge or cheese. "If you forget that both models are nonsense, you might end up publishing a press release declaring a detection of cheese on the Moon," he says.

In an April 18 statement, NASA distanced itself from speculation of life on K2-18 b, saying that the "detection of a single potential biosignature would not constitute discovery of life. We would need follow-up studies and multiple converging lines of evidence to confirm true biosignatures and rule out false positives."

And while DMS is only produced on Earth by life, within the past year teams of researchers have detected DMS on the comet 67P/Churyumov-Gerasimenko, in the gas and dust between stars, and in lab experiments where ultraviolet photons (simulating starlight) react with molecules in a simulated hazy atmosphere. These results suggest that DMS could be produced in banal, nonbiological ways elsewhere in the universe, challenging the idea that DMS is a clear sign of life. –M.Z.

PLANET NINE SEARCH YIELDS UNEXPECTED CANDIDATE

Science textbooks may be in for another revision. Astronomers say they have identified a candidate for an elusive ninth planet beyond the orbit of Neptune — but it may not be the one they were looking for.

In 2016, astronomers proposed that our solar system harbors a massive unseen planet based on a strange clustering of orbits they detected among distant Kuiper Belt objects. They suggested this world is tugging on those objects with the heft of 5 to 10 Earth masses. But so far, there's no direct evidence that the so-called Planet Nine exists.

TWO-FACED. The striking difference between the lunar nearside (left) and farside (right) is evident in these mosaics captured by NASA's Lunar Reconnaissance Orbiter. NASA/JPL-CALTECH

Luna may be lopsided

The same side of the Moon always faces us, but if we could see the farside, it would look like a different world. Where the nearside has vast volcanic basins known as maria, the farside is covered with small craters and looks like a golf ball. The reason for this difference could be a literal imbalance in the Moon, according to research published May 14 in *Nature*.

The discovery was made using data from NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission. In mapping the Moon's gravity, the researchers found that as the Moon orbits Earth, the nearside undergoes more flexing due to tidal forces than the farside does. The tidal forces are the same phenomenon responsible for ocean tides on Earth. While there are no oceans on the Moon, "the surface actually goes through a tidal deformation," says Ryan S. Park, a planetary scientist at NASA's Jet Propulsion Lab in Pasadena, California, and lead author of the paper.

This variation in tidal flexing helps to reveal the Moon's internal structure: a 2- to 3-percent mass asymmetry between the sides, mostly in the mantle. The cause may be heat from deep within the Moon that results from its geologic history, when the nearside was more active than the farside. The difference in internal structure may also lead to more moonquakes on the nearside, where temperatures appear to be hotter. – JOHN WENZ

A new study led by astronomy graduate student Terry Long Phan at National Tsing Hua University in Hsinchu, Taiwan, compared 1983 data from the Infrared Astronomical Satellite (IRAS) with 2006 data from Japan's AKARI mission, searching for faint sources that moved slowly over the intervening 23 years. After analyzing 2 million objects, they identified one promising candidate consistent with Planet Nine's expected properties.

But Mike Brown, one of the Caltech astronomers who originally proposed Planet Nine, says the candidate's highly inclined orbit means it is "100 percent NOT Planet Nine." If the object is real, Brown says, it would not produce the observed clustering of Kuiper Belt objects, and "probably disproves the existence of Planet Nine." Brown says it's also possible the candidate is simply noise in the data or a transient astrophysical event rather than a solar system object.

The mystery may soon be resolved. The newly constructed Vera C. Rubin Observatory will transform our ability to detect slow-moving objects in the solar system, and has "a very good chance" of finding the real Planet Nine, says Brown. – ASHLEY BALZER VIGIL

WRONG PLANET? Planet Nine is depicted as an ice giant in the outer solar system in this artist's rendering. JPL-CALTECH/R. HURT (IPAC)

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Abstract

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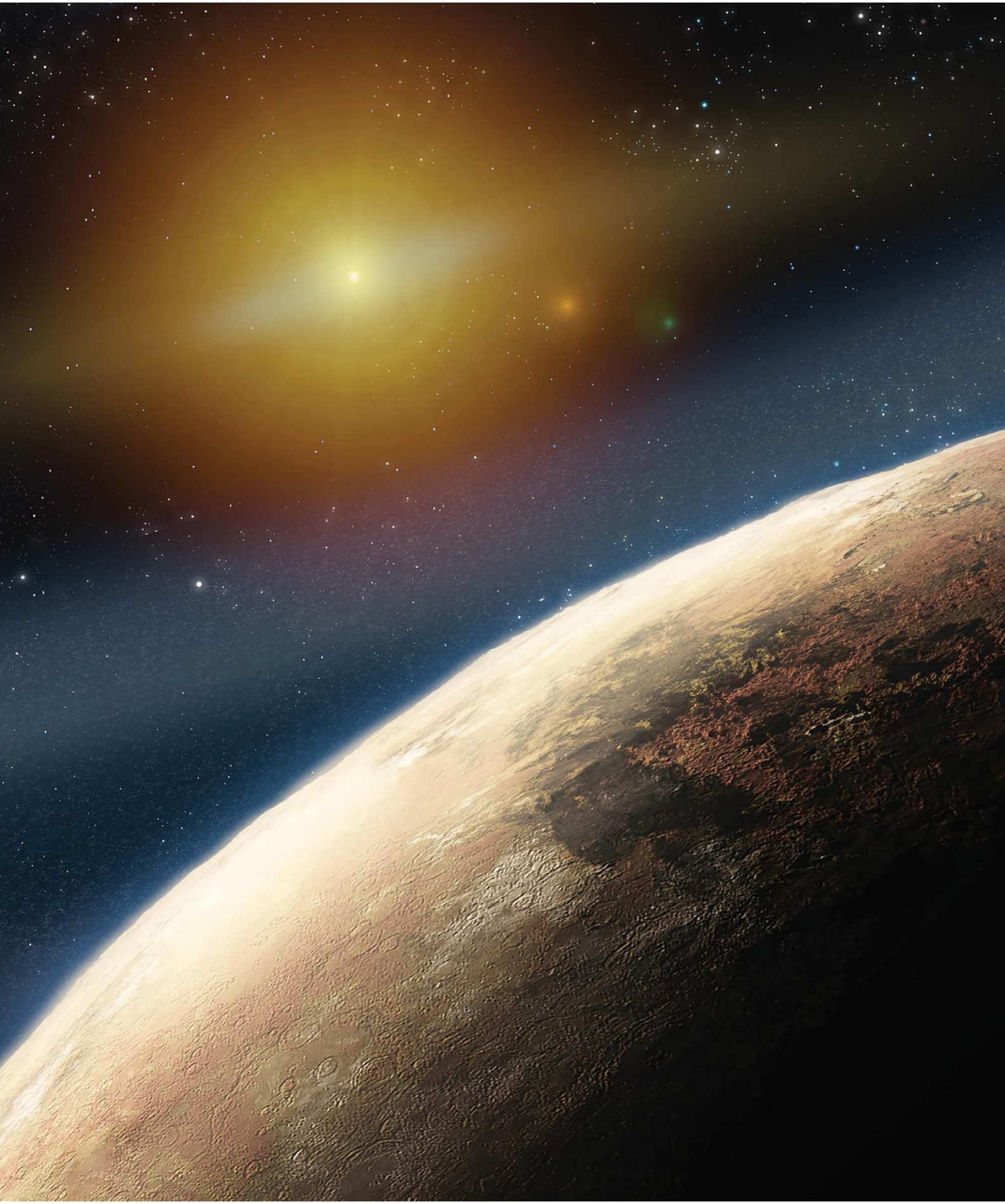
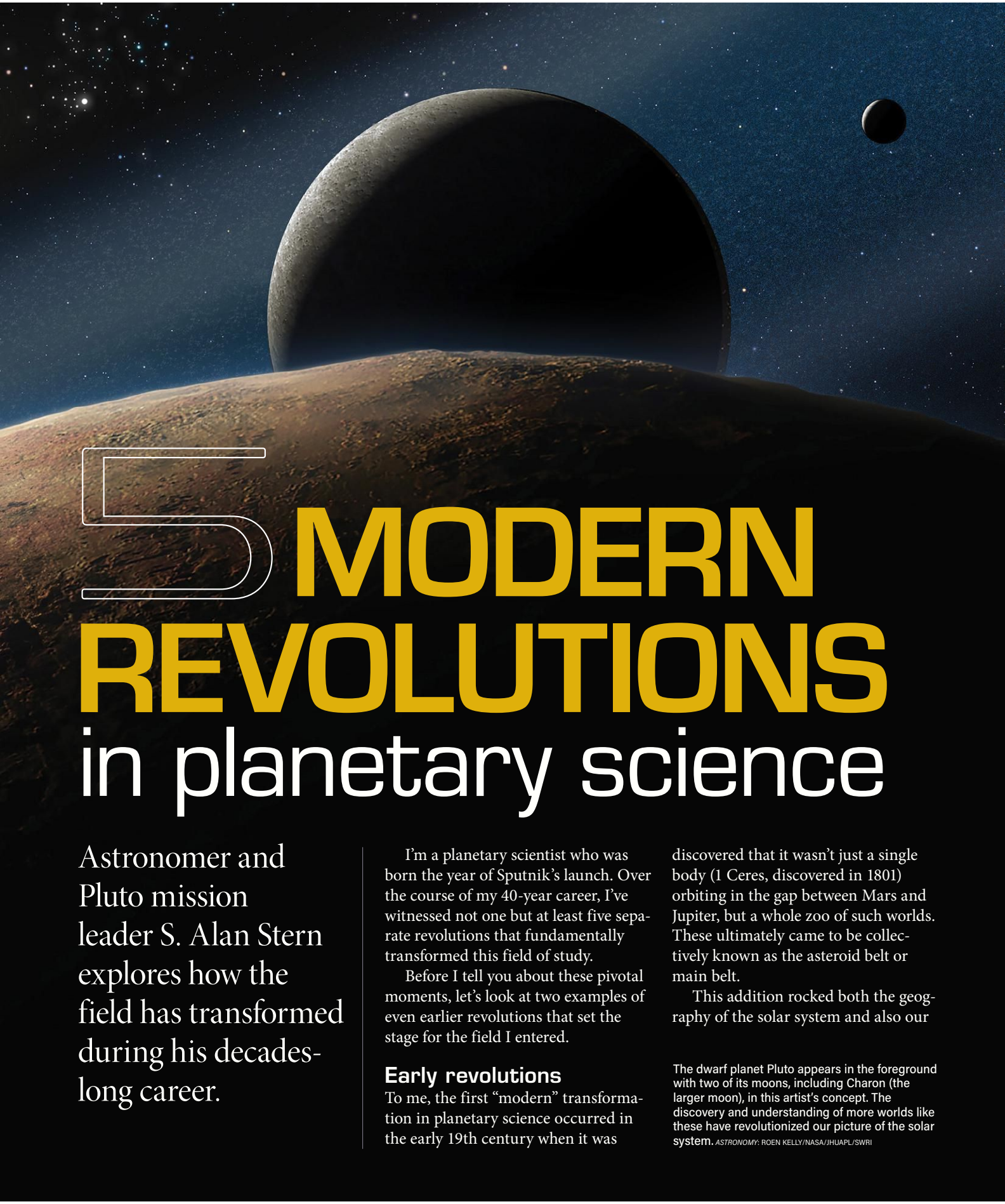




5 MODERN REVOLUTIONS in planetary science

Astronomer and Pluto mission leader S. Alan Stern explores how the field has transformed during his decades-long career.

I'm a planetary scientist who was born the year of Sputnik's launch. Over the course of my 40-year career, I've witnessed not one but at least five separate revolutions that fundamentally transformed this field of study.

Before I tell you about these pivotal moments, let's look at two examples of even earlier revolutions that set the stage for the field I entered.

Early revolutions

To me, the first "modern" transformation in planetary science occurred in the early 19th century when it was discovered that it wasn't just a single body (1 Ceres, discovered in 1801) orbiting in the gap between Mars and Jupiter, but a whole zoo of such worlds. These ultimately came to be collectively known as the asteroid belt or main belt.

This addition rocked both the geography of the solar system and also our

The dwarf planet Pluto appears in the foreground with two of its moons, including Charon (the larger moon), in this artist's concept. The discovery and understanding of more worlds like these have revolutionized our picture of the solar system. *ASTRONOMY*: ROEN KELLY/NASA/JHUAPL/SWRI

knowledge of its content, forcing the realization that most solar system bodies are not planets, but small bodies.

Another early but utterly fundamental transformation in the field was the development of spaceflight in the mid-20th century. This epochal advancement turned planetary science from a backwater of observational astronomy into a major field of its own. Spacecraft enabled us to study solar system bodies with in situ techniques like magnetic sounding and atmospheric and surface sampling. It also delivered imagery with resolution orders of magnitude beyond what is possible from Earth. This, in turn, opened up the fields of planetary geology, planetary meteorology, and other research domains that had been unable to advance via remote sensing from ground-based observatories alone.

I entered grad school and began regularly publishing research results in the mid-1980s. Using that as a start date, I count five truly epochal transformations that have washed over planetary science since then. All five shook the field to its core.

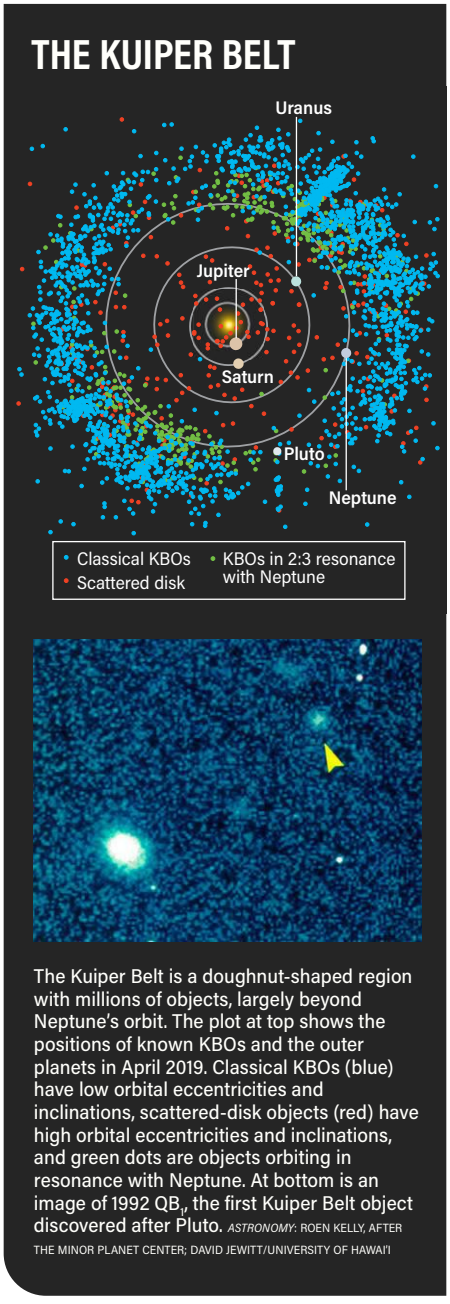
Here's how I've ranked them, in order of importance.

1 The discovery of the Kuiper Belt

The greatest single revolution in planetary science during my time happened in the early 1990s with the discovery of the Kuiper Belt, the third zone of our solar system after the terrestrial planet and giant planet regions.

I rank this at the top because it transformed the field in so many important ways. Like the much earlier discovery of the asteroid belt, the discovery of the Kuiper Belt redrew the map of our planetary system — but in this case, even more fundamentally. The Kuiper Belt enlarged the planetary region dramatically and revealed the source of almost all short-period comets. It also showed that Pluto was not a misfit planet that didn't fit in with the terrestrial and giant planets, but instead was the harbinger of a whole new class of so-called dwarf planets, which we now know outnumber the terrestrial and giant planets combined. And the Kuiper Belt's orbital distribution of bodies crucially also showed us unequivocal evidence that the giant planets migrated dramatically from where they formed to where we see them today.

The discovery of the Kuiper Belt transformed both the architecture and population of our solar system from the quaint 20th-century model of nine planets and an asteroid belt to a far larger, far richer, and far less static solar system that no one had anticipated.



The Kuiper Belt is a doughnut-shaped region with millions of objects, largely beyond Neptune's orbit. The plot at top shows the positions of known KBOs and the outer planets in April 2019. Classical KBOs (blue) have low orbital eccentricities and inclinations, scattered-disk objects (red) have high orbital eccentricities and inclinations, and green dots are objects orbiting in resonance with Neptune. At bottom is an image of 1992 QB_1, the first Kuiper Belt object discovered after Pluto. *ASTRONOMY*: ROEN KELLY, AFTER THE MINOR PLANET CENTER; DAVID JEWITT/UNIVERSITY OF HAWAI'I

2 The discovery of exoplanets

My second-place planetary science game-changer in the past four decades also occurred in the 1990s: the discovery of exoplanets.

Thanks to the rapid advance of this research area since then, we have now identified nearly 6,000 exoplanets. But more importantly, we now know that exoplanets are common to virtually all stars and that planets far outnumber the galaxy's stars.

We also now know that the architecture of our solar system — with four terrestrial planets near the Sun, followed by an asteroid belt and then four giant planets, with a surrounding primordial debris belt (the Kuiper Belt) harboring a variety of dwarf planets — seems to be far from typical. In fact, as more and more exoplanets have been discovered, we've learned that there are many new types of planets not anticipated from studies of our own solar system. These include planets circling pulsars, Jupiter-like worlds close to their stars, "fluffy" low-density exoplanets (as light as balsa wood!), super-Earths, and more.

Many of you and my planetary science colleagues might consider the discovery of exoplanets and their ubiquity to be the No. 1 planetary science game-changer of the past few decades. But it lands at my No. 2 because these bodies lie outside our solar system and can only be studied by astronomical techniques (as opposed to by spacecraft that can visit and study them up close).

TELL US YOUR TOP FIVE

You might be thinking that your list of the top revolutions in planetary science over the past few decades is not the same as mine. That's just fine! In fact, we'd like to hear from you so we can compile a "readers' choice" top five and runners-up list, too. Scan the QR code to visit Astronomy.com and take part in our poll, which we'll use to create the final reader's choice list. Have at it, *Astronomy* hive mind! — *S.A.S.*

3 The discovery of ocean worlds

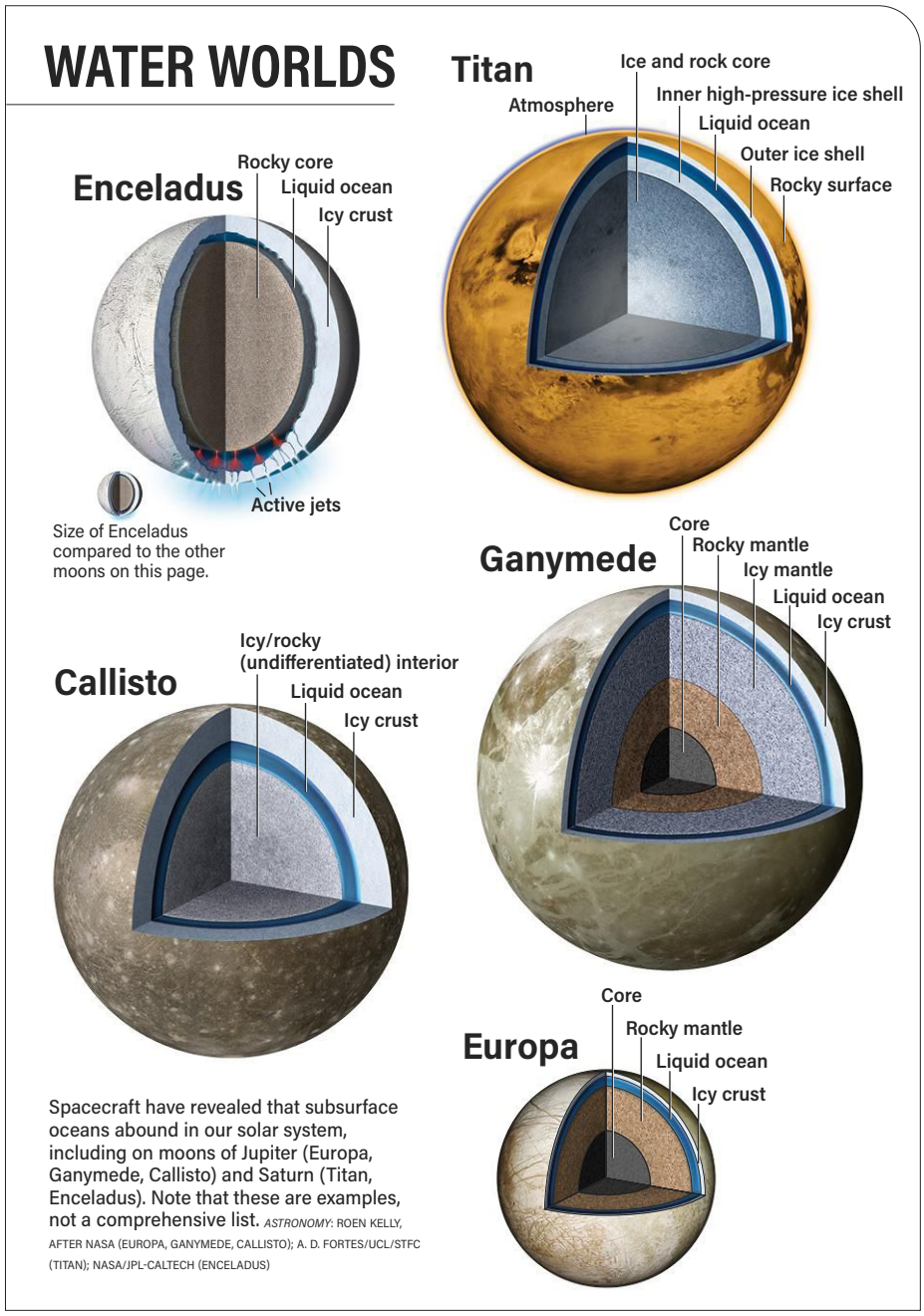
When 20th-century planetary astronomers looked out across our solar system using the tools of their time, they saw no other worlds with oceans and concluded that Earth was unique for this feature. This remained the paradigm for more than a generation.

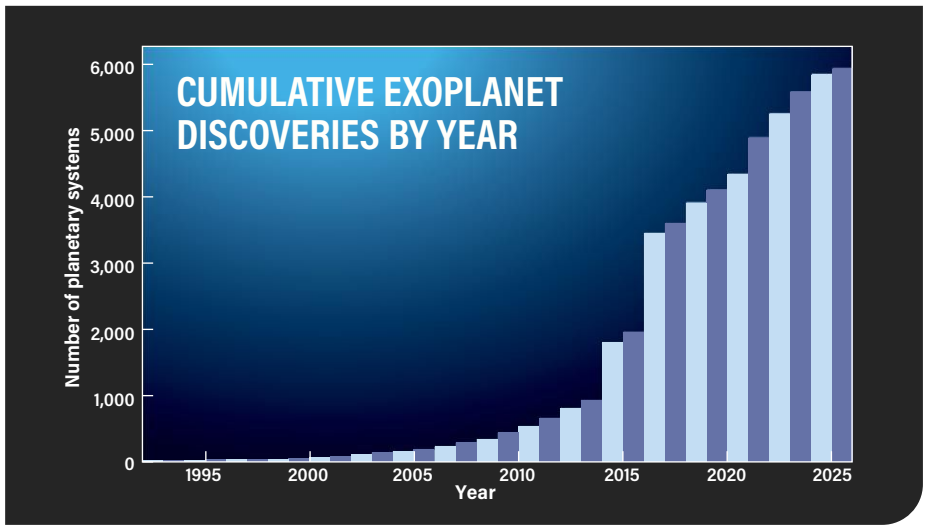
Until it crumbled. Beginning in the late 1990s, a series of spacecraft missions revealed that the solar system does, in fact, contain other ocean worlds. But these oceans are not like ours because they lie underneath (rather than on top of) their world's crust.

This revolution began when NASA's 1990s Galileo orbiter found unequivocal evidence for a water ocean beneath the surface of Jupiter's moon Europa, based on induced magnetic fields in the moon. By the mid-2000s, NASA's Cassini mission had also found saltwater plumes emerging from Saturn's moon Enceladus, irrefutable evidence for a subsurface ocean there as well. Today, we see strong evidence for subsurface oceans in many other icy satellites and also among the dwarf planets, ranging from Titan to Triton, Ceres to Pluto, and others.

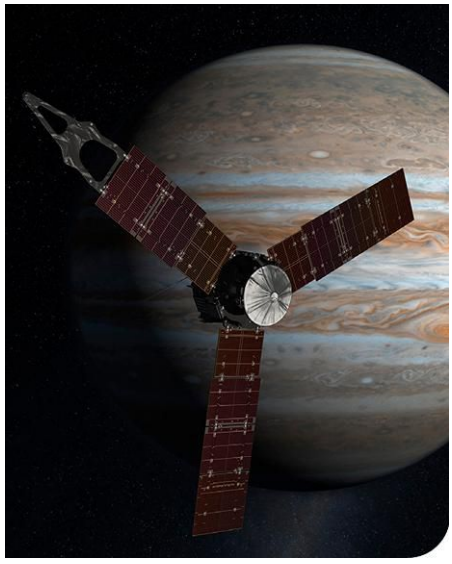
With the discovery of so many ocean worlds, the possibility of the development of life in them has driven astrobiologists to place these worlds high on the priority list for more detailed study. This push has led to missions like NASA's Europa Clipper and the European Space Agency's JUICE, which will explore the Galilean satellites.

The discovery of ocean worlds across our solar system also challenged the notion that life can exist only within a Goldilocks-like, narrow habitable zone near our star, turning that paradigm on its head as we discover potentially habitable worlds at least as far out as the Kuiper Belt. The 20th-century view that Earth was our solar system's only ocean world has now been shattered; all these other ocean worlds with water beneath their surfaces simply escaped detection until spacecraft found them through





This histogram shows the cumulative number of confirmed exoplanetary systems by year. ASTRONOMY: ROEN KELLY, AFTER EXOPLANET ARCHIVE (HTTP://EXOPLANETARCHIVE.IPAC.CALTECH.EDU/)



Over the past 40 years, NASA has transitioned to missions led by principal investigators rather than project managers. Some examples of these PI-led endeavors in the field of planetary science include the Juno mission to Jupiter (near left), the OSIRIS-REx asteroid sample-return mission (far left), and Mars Pathfinder (above). NASA/JPL; NASA/GODDARD/UNIVERSITY OF ARIZONA; NASA/JPL

in situ investigations. As a result, we now know that ocean worlds are common in our planetary system, and we suspect the same is true across the universe.

What is uncommon in our solar system, it now turns out, are worlds that wear their oceans on the outside like Earth — another idea never anticipated before this revolution.

4 The rise of PI-led missions

It's worth saying that not all of the planetary science revolutions I have witnessed were game-changing discoveries or shifts in scientific paradigms. There have also been two major changes in how planetary science is done.

The first of these was the rise of missions led by a PI — a principal investigator, or scientist. This is now the dominant mission type in U.S. planetary science, but prior to the 1990s, no planetary scientist led a space mission to any world, no matter how close or far, no matter how small or large. Instead, all planetary missions were led by project managers, or PMs. The science team — usually led by a single project scientist — reported to the PMs, who were not scientists but instead were engineers or even professional managers. This often put science in the back seat because the mission's science objectives were throttled by non-scientists at the helm.

However, starting in the late 1990s, NASA began developing a new kind of mission, led by a PI scientist to whom the PM (and everyone else) reported. It was seen as a smarter way to do science missions. NASA has now selected nearly 30 PI-led missions in our solar system, all but one of which have been successful. Compare that with just four non-PI-led NASA planetary missions chosen in the same time frame.

Through NASA's Discovery and New Frontiers programs, the PI-led paradigm has almost completely replaced older PM-led missions. Putting a scientist in charge has transformed how planetary science is both led and accomplished.

5 The rise of commercial spaceflight

The other factor that has changed how planetary science is done is the rise of commercial spaceflight. This has already transformed the launch business by making launcher reusability routine, significantly lowering price points and dramatically raising launch rates. These changes have opened up a wide variety of new use cases in the space economy.

Commercial involvement is also transforming the way space missions are tracked and how they communicate with Earth, by developing ground- and space-based tracking and communications networks that are replacing traditional government networks like NASA's Tracking and Data Relay Satellites and ground stations. This has vastly increased network bandwidth capacity while also reducing mission costs.

Equally important are the first glimmers of commercial interplanetary space missions. So far, we have seen the first small commercial missions planned or operated to the Moon, Venus, and asteroids while NASA has called for innovative commercial solutions to restructure its dysfunctional Mars Sample Return megaproject.

Simply put, the commercial space revolution has sparked a sea change in how

missions are completed by replacing the older government-only mode that opened space in the first era of exploration beyond Earth. The development of commercial spaceflight, in many ways, parallels the revolution in computing that occurred when old-school mainframes gave way to proliferated, less expensive, and more capable PCs. We can't really predict how commercial spaceflight will transform planetary exploration in the coming decades, but I suspect this revolution is only in midstride.

What's next?

This retrospective now begs the question of what the biggest discoveries of the next 40 years might be. Experience teaches us that any such predictions are likely to be wrong, or at least naïve. Nonetheless, I'll venture to suggest some possibilities.

In terms of scientific discoveries, perhaps we will find life on one or more of the solar system's ocean worlds. Or maybe we will uncover multiple planets within the outer Oort Cloud, which lies far beyond the Kuiper Belt. Or both.

The way we do research will likely change as well. Just as most terrestrial geologists are now employed by private sector resource and energy companies, commercial space could eventually employ more planetary scientists than academia and government agencies combined.

Other changes to come could be that advanced propulsion dramatically shortens trip times across the solar system, making its worlds more quickly and routinely accessible. And we might find that humans will be working in many locales around the solar system within the next few decades, and that artificial intelligence is doing much of the scientific discovery that was once only the provenance of humans.

Looking back over the time I've spent in this field, it's hard to believe how much our view of the solar system and the way we should explore it have changed. It's also hard to believe how the field of planetary science has grown. In the mid-1980s, there were perhaps 1,500 practicing planetary scientists in the world. Today, there are well over 10,000!

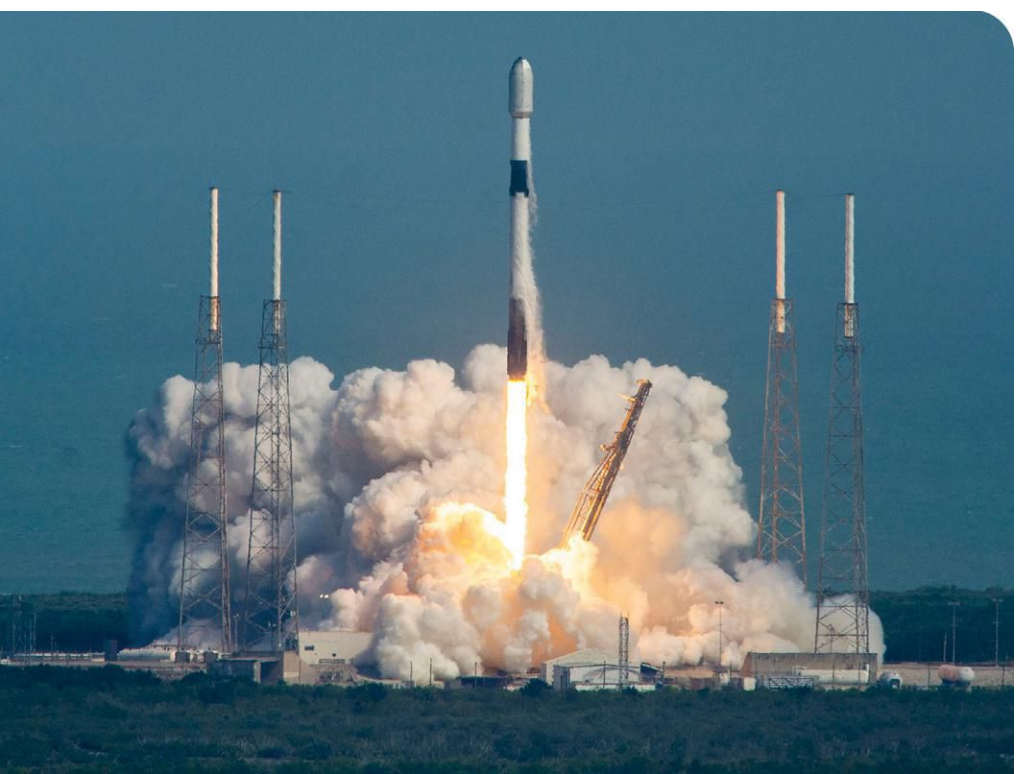
The march of technology, the much greater workforce size, and the proliferation of countries and companies involved in spaceflight have all accelerated the pace of change in planetary science over the decades. I expect these trends to continue. And I can't wait to see what the next few decades of discovery will bring!

S. Alan Stern *is a planetary scientist, aerospace executive, speaker, author, and commercial space astronaut. He lives near Boulder, Colorado, and works for the Southwest Research Institute and a number of consulting clients.*

THE RUNNERS-UP

There were seven runners-up to my top five list. Here they are, in no particular order.

- In the 1980s, we discovered that Saturn's rings are not unique. In fact, rings are common among all the giant planets of our solar system, and even (as we discovered in the 2010s) extant around small bodies like Centaurs and dwarf planets.
- Also in the 1980s came the general recognition that Earth's Moon was formed by a giant impact with a planet-sized intruder that struck Earth to spall off Luna. Moreover, we accepted that impacts like this also helped shape Mercury's present-day structure, formed the Pluto-Charon binary, and may have tilted Uranus and Neptune's poles.
- We have discovered numerous satellites around asteroids, not one of which was known before the Galileo mission's groundbreaking discovery of the moon Dactyl orbiting the small main-belt asteroid 243 Ida in 1991.
- There is now strong forensic evidence that the giant planets of our solar system migrated considerably into their current positions after forming, and that a fifth giant planet might even have formed among the four giant planets we see today.
- I also considered the discovery that the Moon's poles possess large quantities of water ice, something conjectured but not proven until the 1990s and 2000s.
- Scientists rarely travel to use big telescopes anymore, even though there are now many more of these facilities than in the past. Instead, most large telescope work is done remotely, while sitting at home!
- We've discovered that small planets like Pluto can remain wildly geologically active more than 4 billion years after their formation. This finding broke the paradigm that isolated smaller worlds generally cool off and all but die, geologically speaking, not long after forming.



A SpaceX Falcon 9 rocket lifts off from Cape Canaveral in Florida in March 2023, carrying a set of 56 Starlink satellites. SPACEX (CC BY-NC 2.0)

Why you can't

Our visual processing systems evolved to keep us alive on Earth, but often fail when interpreting events in the sky.

BY DONALD GOLDSMITH

"WHO YA GONNA BELIEVE — me or your own eyes?" This famous challenge appears in a scene from the 1933 film *Duck Soup.* Chico Marx's character, in a delightfully ridiculous act of espionage, has dressed himself identically to Groucho, in a nightcap and long nightshirt. A formidable dowager played by Margaret Dumont has just seen Groucho leave her room and tells Chico, as he emerges from under her bed, "I thought you left." He denies it. "But I saw you with my own eyes," she replies, only to be contradicted by Chico's famous statement, often misquoted as: "Who ya gonna believe — me or your *lying* eyes?"

Dumont's character's belief in the validity of her observation reflects a deep conviction that each of us possess the ability to see the world clearly. But in unusual circumstances, our ability to interpret our surroundings based on what we

trust your eyes

see often evaporates. Coming to terms with this is an unwelcome task (and a blow to our self-esteem) that requires serious thought.

For astronomers, the effort is worthwhile. History has repeatedly shown that we humans are imperfect observers, susceptible to enhancing our perceptions with illusory, fantastical flourishes, whether by the unaided eye or peering through the eyepiece of a telescope.

The illusion of vision

The belief that what we see must be real ignores the process by which we "see" anything. First, light must pass through our eyes' lenses and strike our retinas, impacting our rods and cones and creating signals that travel through our optic nerves into the visual cortex of our brain. There these signals undergo interpretation that leads to our sensation of vision.

None of these channels involve a perfect image of the world outside, but the final step is the most subjective. Like most animals, our survival hinges on our ability to interpret the world around us as rapidly and coherently as possible — a capacity that has evolved over millions of years. As a result, our

Venus — one of the most frequently misidentified objects in the sky — appears at dawn low on the horizon in this image alongside a crescent Moon, with the Pleiades (M45) star cluster above them. ALAN DYER

RIGHT: Reports of moving and shifting lights in the night sky often turn out to be airplanes flying in standard traffic patterns. JOHN MURPHY/ WIKIMEDIA COMMONS/ CC BY-SA 2.0

ABOVE: The difficulty of interpreting distances in the night sky can be demonstrated by the objects M97 (bottom right) and M108 (top left) — similar in apparent brightness and size. But while M97 (also known as the Owl Nebula) is a planetary nebula lying 2,600 light-years away, M108 is a galaxy 30 million light-years away. GREG MEYER

brain acts as a modeling device, trained in instantaneous, subconscious interpretation of the signals it receives.

The study of how our brain converts raw data from our retinas into quick impressions began in earnest with 19th-century German physicist-physician Hermann von Helmholtz, most famous in his era for inventing the ophthalmoscope that allowed doctors to look inside a human eye. Helmholtz concluded that human eyes cannot physically produce images as sharp as those that are manifested by the brain. Instead, he argued, our brain uses our past experiences to create sharp images and visual impressions.

In most cases, these inferences occur unconsciously. At times, we may recognize that we have the time and opportunity to analyze what we may be seeing, and to draw conscious conclusions about its nature. But in all cases, everything that we see represents an illusion — quite different from a "pure" record such as an undoctored photograph.

Our evolutionary need to fit new phenomena into our preset matrix of how the world works transforms what usually supplies a great advantage — our years of experience — into a serious drawback: our inability to see unusual events as they really are. Our brain wants the world to make sense and tells us stories toward this end. The stories may describe what actually exists, but we cannot be confident that they always do so.

Helmholtz coined the term "unconscious inference" to describe this phenomenon. But his work was largely dismissed by scientists and philosophers who favored a more objective view of perception.

Common errors

A century later, the British neuroscientist Richard Gregory led a revival of interest in Helmholtz's work. He cited Helmholtz to argue that resolving the ambiguity of the images on our retinas requires prior knowledge of the world. (Incidentally, Gregory was an amateur astronomer and his father, Clive, founded what is now the University College London Observatory.)

Of particular application to sky events, Gregory emphasized that we cannot determine the size, shape, and distance of objects from our retinal images alone. For instance, a small object at a close distance will span the

same angular distance as an object that is 10 times larger and lies 10 times farther away. Almost every report that states the size and distance of an object in the sky deserves an immediate question: How do you know?

Another mistaken and somewhat subtler conclusion arises from our unfamiliarity with three-dimensional motion in the sky. Because our brain interprets the sky as a basically flat surface, an aircraft headed directly toward us at a constant altitude will appear to hover and then rise straight upward.

light clouds skim across the sky and suddenly reveal Venus, the planet can appear to have its own motion. Even when it looks stationary, Venus still heads the list of objects mistakenly reported as unusual. For those unfamiliar with the night sky, it may seem to have appeared suddenly. Atmospheric refraction can change Venus' color, and if you jump in your car to follow it, Venus will maintain an unchanging distance from you, no matter how fast you drive.

But what about expert observers of the sky? Can we rely on,

TOP: Hermann von Helmholtz (1821–1894) proposed that vision is in part constructed by our brain and past experiences. ALTE NATIONALGALERIE, STAATLICHE MUSEEN ZU BERLIN/ ANDRES KILGER

BELOW LEFT: Viewing with his 24-inch Clark refractor, Percival Lowell was convinced that he saw canals created by an intelligent civilization on the surface of Mars, which he recorded in this sketch published in 1895. PUBLICDOMAINREVIEW.ORG

BELOW RIGHT: The interpretation of these features as linear channels lingered in scientific discussions until the mid-20th century, as shown in this 1962 map of Mars published by the U.S. Air Force with the assistance of Lowell Observatory's Earl Carl Slipher. While Slipher rejected Lowell's idea that the canals were created by intelligent life, he thought they were instead a form of vegetation. It wasn't until Mariner 4 flew by Mars in 1965 that the planet's arid surface was revealed and the canals were confirmed to be illusory. AERONAUTICAL CHART AND INFORMATION CENTER/LIBRARY OF CONGRESS

The study of how our brain converts raw data from our retinas into quick impressions began in earnest with 19th-century German physicist-physician Hermann von Helmholtz, most famous in his era for inventing the ophthalmoscope that allowed doctors to look inside a human eye.

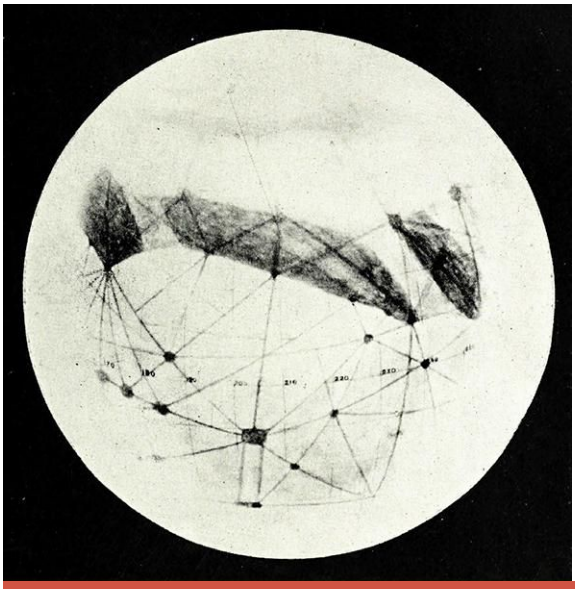
Both of these errors can appear when a bright meteor seems to strike the ground just over the next hill, when in fact it passed overhead at an altitude of dozens of miles and landed, if at all, at a similar distance from us.

The subconscious processing in our brain introduces other types of errors, such as in judging whether an object is moving or stationary. For example, when

say, airline pilots, to do better at analyzing truly unfamiliar objects? After all, pilots must concentrate on complex tasks within a changing environment, laden with responsibility for correct judgment. But studies show this does not increase their capacity for judging unusual objects or events. As pilots are experts in the regular appearance of the skies, they are indeed skilled at

recognizing strange events as unusual. But they often have no more expertise in understanding what these events actually are than the general public does.

An additional problem confronts both pilots and the general public in their attempts to appraise unusual events in the skies: their rapid appearance and disappearance. The difficulties that we face in processing



unfamiliar events grow larger when we must do so quickly, sometimes within a few seconds. This hardly allows our brain the chance to consider carefully any such event. Anyone who has joined friends to watch a meteor shower has learned the uselessness of crying "Look at that!" because almost no meteor lasts long enough for others to see it.

Nature and nurture

In addition to the perceptual processing that results from human evolution, any person experiencing an unusual event is also affected by their personal history and beliefs.

Consider Percival Lowell, a highly intelligent and skilled astronomer who built his eponymous observatory in Flagstaff, Arizona, in the 1890s around a 24-inch Clark refractor. He was particularly motivated to study Mars, largely because of his belief that extraterrestrial life flourished there.

When Lowell's brain turned various features on the martian surface into elaborate networks of canals, he was responding both to our subconscious tendency to link random dots into continuous patterns and also to his innate convictions. Confronted with the fact that much larger telescopes, such as Lick Observatory's 36-inch refractor and the 40-inch refractor at Yerkes Observatory, failed to show the features that he had drawn, Lowell insisted that their lenses were *too* large.

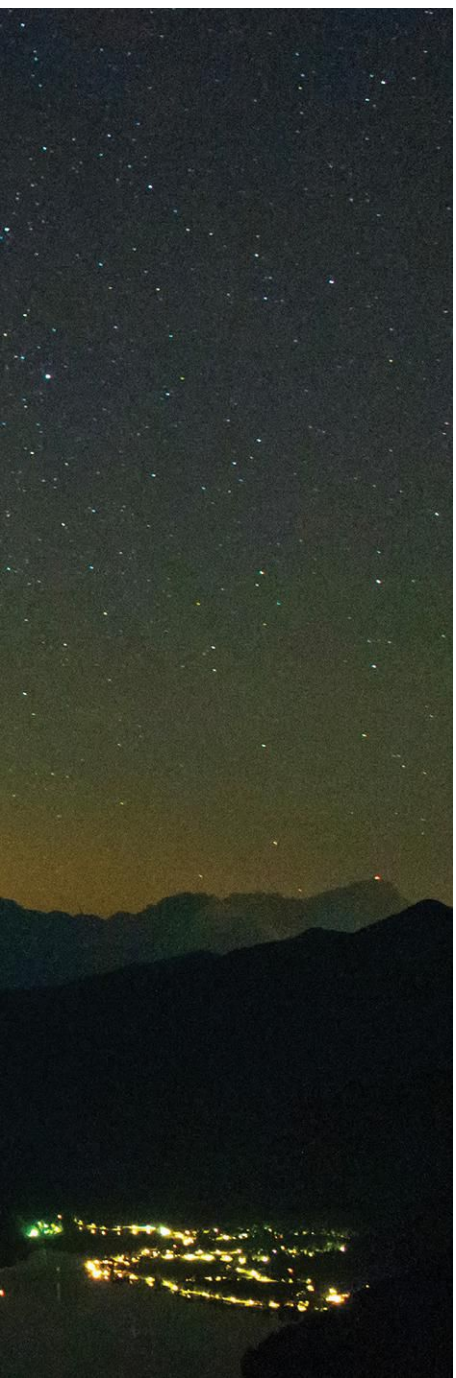
Lowell's attitude and explanation well conform to the old, only slightly cynical adage, "I'll see it when I believe it." It is an

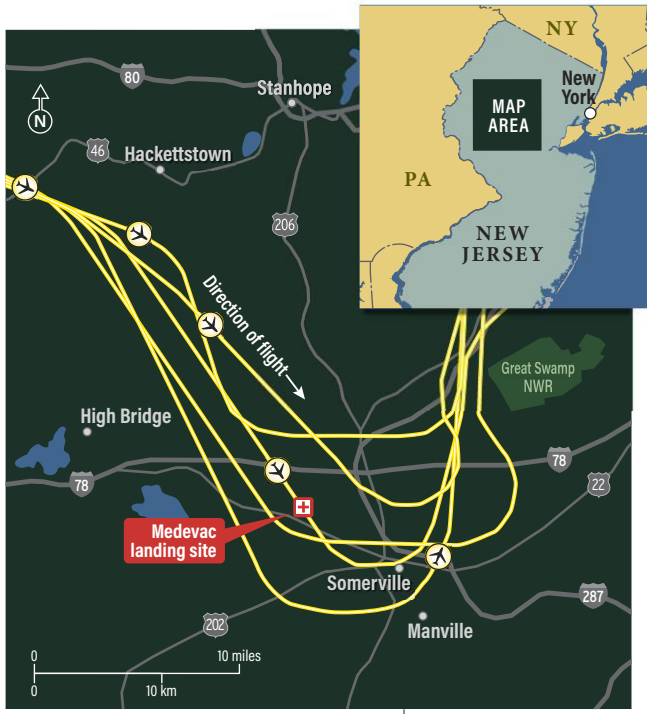
The fleeting nature of meteors can make them difficult to process, but noting their time can help corroborate your report with those of others. ARMAN MORADI FARD

intriguing aspect of human behavior that almost none of us recognize this propensity in ourselves.

Pre-existing convictions such as Lowell's influence many of those who report strange celestial events. Unsurprisingly, any of us may carry subconscious or conscious judgments about what might appear in the sky from a lifetime of exposure to provocative suggestions from the entertainment industry.

One more aspect of our human development can cloud the accuracy of what we have seen in the sky: If a group of people observe an unusual event, one person's deeply held conclusion may gain widespread acceptance among those with less certain opinions. With the advent of social media, this effect is more powerful than ever — as demonstrated in November and December 2024 over New Jersey and several other states in the U.S., when numerous observers reported unusual objects in the sky. As these turned out to be almost entirely aircraft and authorized drones, public interest first waned — and then vanished.





At night, airplanes can sometimes appear to be hovering in formation or moving erratically when in fact they are following established traffic patterns. On Nov. 26, 2024, in Somerset County, New Jersey, a medical helicopter was forced to abandon an evacuation when observers on the ground spotted what they thought were three drones hovering near the makeshift landing site. Investigators later concluded from an analysis of flight tracking data that the "drones" were three commercial aircraft up to several miles away moving directly at the observers, approaching a nearby waypoint.
ASTRONOMY: ROEN KELLY, AFTER TRANSPORTATION SECURITY ADMINISTRATION

Clear-eyed observations

In view of the concatenation of influences described above, what hope remains for gaining an accurate understanding of strange events in the sky? Our finest instrument in this quest — our marvelous brain — confronts a long list of difficulties in achieving this goal. Our evolution, our lack of experience in studying the sky, the rapidity with which events occur, our inability to apply trigonometry to what we see, and our internal convictions about what we ought to see all work against a reasonable belief that we accurately know what we have seen.

But there is one key piece of objective information that any observer can record: the time of an event. Although we have no control over the long string of events that leads to our brain processing an unusual sight, we can easily note the time of its occurrence (unless we left our smartphone or watch at home).

Accurately timing an event gives experts a far better chance to determine its cause, provided that observers have independent experiences. With this information, it's relatively straightforward to determine whether observers have seen human-made events or objects, such as a train of Starlink satellites or the plume from a rocket launch. Rockets now often ignite an upper stage, either to increase their payload's velocity or to allow a booster rocket to descend safely to Earth, producing a sudden trail of light visible over a thousand-mile range. These events can also occur thousands of miles from the actual launch sites. Comparison of an observer's recorded time with the time of launch or ignition provides the surest check on whether the sudden excitement in the sky has a human origin.

So the next time you see something strange in the sky, don't just believe your own eyes: Mark the time and place, and remember the complex process by which your brain creates what you are seeing. Understanding the limitations of visual perception doesn't mean we should stop looking up in wonder. Instead, it invites us to do so with greater awareness of how we see the universe around us.

Donald Goldsmith *is an astronomer and science writer in Berkeley, California. His latest books are* Exoplanets *and* The End of Astronauts: Why Robots Are the Future of Space Exploration *(with Martin Rees).*

ROSETTE NEBULA (NGC 2244)

Getting started with REMOTE IMAGING

Setting up a remote observatory allows you to gather images from the comfort of your home.

STORY AND IMAGES BY FRANK DIBBELL

MOST OF US DO NOT live in a dark-sky area, or even close to one. Often an imaging session involves loading a ton of equipment into a vehicle and driving for several hours to a less light-polluted site. We arrive at the destination, unload the equipment, and set it all up — only to discover we've forgotten something. Or, worse, clouds move in.

If all that sounds familiar, then you can see why remote imaging has become so popular. Perhaps you, too, have considered hosting your equipment at a location dedicated to serving the needs of imagers.

With remote imaging now available to professional and amateur astronomers alike, there are several options available to you. If you don't own a lot of expensive equipment, there are subscription services where you can rent time on a remote system or purchase datasets for your own use. Cooperatives also are available if you're looking to jointly run a remote system with other amateurs. However, this article is for amateur astronomers who wish to use their own equipment in a semipermanent setup so that they may access it on any opportune night.

A remotely hosted system has many benefits: There's no need to make a long journey, no equipment to set up and align, and no frustrated drives back home if inclement weather arises. You can image in the safety and comfort of your home and retire for a good night's sleep at a reasonable hour. But there are many details to consider before opting to observe remotely.

CHRISTMAS TREE CLUSTER (NGC 2264)

WIZARD NEBULA (NGC 7380)

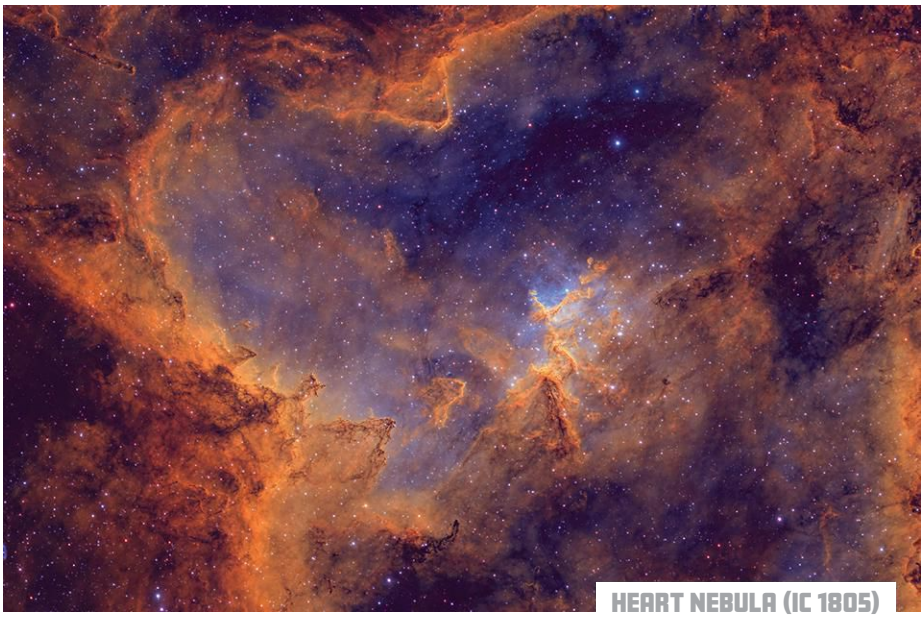
Check your list

First, consider your equipment — both the physical hardware and the software to run it. It's important to remember that you won't have the option to go outside and adjust something if an issue pops up, so you need equipment that is robust, reliable, and state of the art. A typical imaging kit will consist of the following hardware:

- ☐ Imaging telescope
- ☐ Mount
- ☐ Tripod or pier
- ☐ Camera and filter wheel
- ☐ Electronic focuser
- ☐ Rotator
- ☐ Guiding system
- ☐ Flat panel
- ☐ Dew heater
- ☐ Uninterruptible power supply
- ☐ Web power switch
- ☐ Powered USB hub
- ☐ Minicomputer

Almost any high-quality telescope will work as your photon collector. The centerpiece of your imaging kit will be the mount, plus a sturdy tripod or pier to connect it to. You want a mount designed for robotic use, such as an Astro-Physics Mach2GTO or 10Micron series mount. These mounts come with absolute encoders, so if the power is lost, the mount will know where it is when power is restored. Alternatively, other mounts have home positions — a location the mount can be commanded to go to if there's a loss of power.

LEFT: The author's remote-imaging rig combines a telescope and mount with hardware designed to allow access from anywhere in the world.



HEART NEBULA (IC 1805)

Next is the imaging train itself. This can consist of several items: camera, filter wheel, field rotator, electronic focuser, and either an off-axis guider or an external guide scope. It's also important to have a dew heater as well as either an electronic flat panel or lens cover to protect the optics when the scope is not in use. Most remote sites sit on high desert plateaus where it can get quite windy at times, which can kick up a lot of dust, so you'll want your optics protected.

There are also power distribution requirements. Most remote facilities require an uninterruptible power supply and recommend a web power switch so that you can recycle power to your equipment remotely if it's inadvertently shut off. Several companies manufacture power distribution and USB hub solutions, such as PrimaLuceLab and Pegasus Astro, which allow you to connect all your USB devices and 12-volt DC power cords to a common box on top of the scope. Such a setup aids greatly in cable management as well.

Finally, you'll need a computer to run all this equipment. I use a MeLE Quieter 4C — it's compact, has no moving parts, and can easily sit on top of a scope. Having the computer sit atop the imaging kit means one cable fewer hanging off the system. Various brands of minicomputers are available and they usually cost around $200.

Take out your remote

The glue that holds the imaging kit together and allows you to operate it remotely is the software. In addition to the drivers that allow you to access your equipment, you will also need applications to run your imaging equipment and access your remote computer. Two common applications are Sequence Generator Pro and Nighttime Imaging 'N' Astronomy (NINA). Applications like TeamViewer, RustDesk, and Remote Desktop allow you to connect to your remote computer. I recommend having two such applications installed on your remote system.

Before setting any of this up remotely, it's important to thoroughly test your system at home to make sure it all works as you think it should. You will want to set up the imaging system — in the backyard will suffice — load all your software onto the minicomputer, access your minicomputer remotely, and set up an imaging sequence. Make sure to consider the following: (1) how close the mount should get to the pier before performing a meridian flip, (2) the position you want to use for parking the scope, and (3) what should happen if you lose power. It's best to make a list of all the things you want to do, such as the types of images you want to take or the maneuvers you want the scope to be capable of, plus all the things you think could go wrong and their solutions, and test them. Document your system thoroughly with photos and instructions for proper setup when you do get to your remote site.

Location, location, location

You're now ready to choose a remote site. Here are some factors to consider when making that decision.

Location is everything: You want a

The author's New Mexico remote-imaging site is home to several observatories with roll-off roofs.

Deep Space Products Remote offers a facility with basic appliances for guests, whether they are staying several hours or several nights.

The Deep Space Products Remote site in New Mexico is a great example of an ideal remote-imaging location, with dry weather and little light pollution from nearby cities.

hosting site that has dark skies with little to no light pollution, plus good transparency and seeing. Hosting facilities can be found in the American Southwest, specifically in the southern parts of Arizona, New Mexico, and Texas. These areas of the country enjoy all those preferred features plus 300 or more nights of clear skies. Research the weather carefully, because no site is immune to bad weather. While the southwestern deserts have many clear winter nights, the summer brings the monsoon season with rain in July and August.

Costs for hosting sites vary depending on location and observatory size. I have my kit set up at Deep Space Products Remote, located in Animas, New Mexico, in a roll-off roof observatory that's shared with three other kits. I pay $600 a month to rent this pier, which is a fairly typical rate. Also check payment options — some facilities rent month to month with a first and last month's rent agreement, others lease for a year at a time and give discounts for longer leases.

Security at the hosting site is also important. Ask about the nature of site security, whether there are personnel present, and whether the site is monitored regularly.

Technical support is particularly vital when it comes to remote imaging. As thoroughly as we may test our systems, nothing can prevent a USB cable from failing or a slewing error from crashing the scope into the pier. Ask about the level of support the hosting site provides: Is it available on site? What is the average response time, and how are issues reported? Also ask whether there are additional fees associated with certain types of support.

Similarly, what is the nature of the hosting site's technical infrastructure? How do they report safety issues to your kit? For example, if wind gusts or clouds close the observatory, how is your system notified so it can properly shut down? How often does the facility close for maintenance? Are power outages common? Will the facility staff assist you in recommending proper equipment for the environment?

An agreement with a hosting site will involve signing a contract. Like any lease, this contract outlines your rights as a customer as well as the site's responsibilities. It's prudent to receive an advance copy and review it. Some facilities may restrict how you can use your data, so any agreement should be read carefully.

Finalizing your cozy setup

Most sites allow clients to visit (by appointment) and have facilities to host them. This is important because it usually takes more than a day to set up your equipment and properly test it before departing, and it could take even longer if you arrive during a spate of bad weather.

As an alternative, you might ask if it's possible to ship your equipment to the remote site and have them set it up. If you take the latter route, then proper documentation on how to set your equipment up, along with an inventory list and photographs, is critical; the remote site will need this to correctly set up your kit. Remote hosting sites will charge extra for this service, however, and you will have to weigh this fact and any shipping charges against what it would cost you to travel to the site to do it yourself. In my case, it turned out to be cheaper to ship my equipment and pay to have it set up than to do it myself.

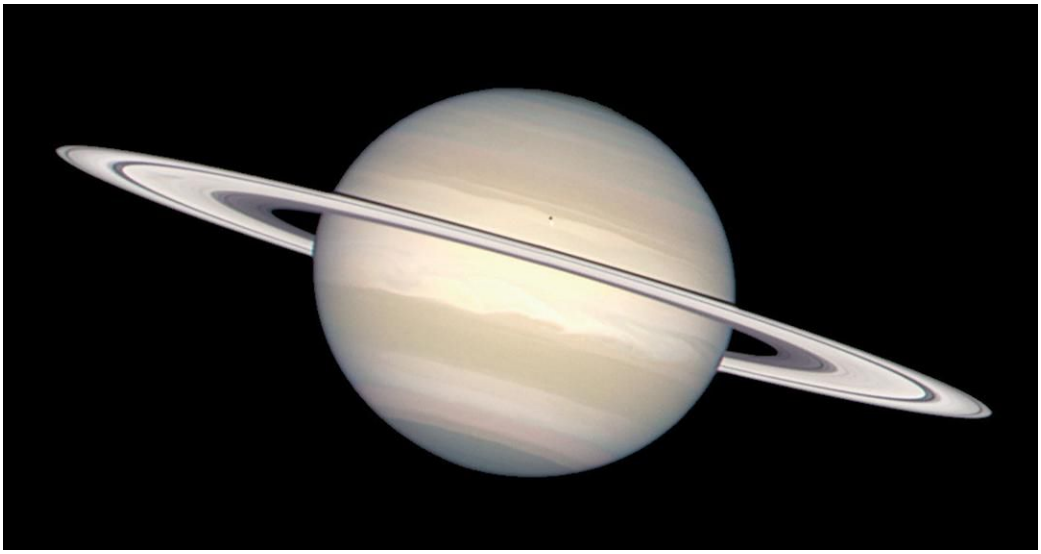
Taking the time to do your research and finding a hosting site that meets your needs will provide you with a fantastic remote-imaging experience. You can finally say goodbye to long drives to merely semi-dark skies, fumbling with equipment, and staying up late in the cold. Now you can image all night long, Moon and weather permitting, any night of the year from the comfort of your own home.

Frank Dibbell *is an avid imager and docent at the local community observatory in Placerville, California.*

SKY THIS MONTH

Visible to the naked eye
Visible with binoculars
Visible with a telescope

THE SOLAR SYSTEM'S CHANGING LANDSCAPE AS IT APPEARS IN EARTH'S SKY.
BY MARTIN RATCLIFFE AND ALISTER LING



The mighty planet Saturn reaches opposition this month, showing off narrow rings and plenty of moon transits. This Hubble image captured a transit of the moon Enceladus with its shadow, roughly centered together above the rings. HUBBLE HERITAGE TEAM (AURA/STSCI/NASA/ESA)

SEPTEMBER 2025

Saturn at opposition

September's sky is rich with opportunities. Titan's shadow continues to transit Saturn. The ringed planet reaches opposition along with Neptune, with both worlds in the same region of the sky. Mars is descending toward solar conjunction. Uranus is a fine binocular target, while Jupiter dominates the early morning. Venus starts the month near M44, then inches closer to a conjunction with Regulus and the crescent Moon.

Mars continues its long slide toward solar conjunction in early 2026 and is visible low in the west after sunset. It shines at magnitude 1.6 in Virgo. On Sept. 11, Mars is 2.4° north of Spica, which shines at magnitude 1.0. Both star and planet set before 9 P.M. local daylight time, and you'll need a clear western horizon to spot them. Mars is too small to see any appreciable detail visually.

Neptune and Saturn remain near each other in the sky. They rise before 9 P.M. local daylight time in early September and by 6:30 P.M. on the 30th. Both reach opposition this month.

Saturn, in Pisces, moves toward Aquarius, arriving the 29th. There are a half-dozen 5th-and 6th-magnitude stars in the vicinity, making a great view in binoculars. The Sept. 7 Full Moon rises half an hour before Saturn, with 9° between them.

Saturn shines at magnitude 0.6 and reaches opposition Sept. 21. This is the closest it gets to Earth: 794.8 million miles away. In a telescope the disk spans 19", while the narrow rings, tilted by only 2° to our line of sight, span 44". Their low tilt offers a broad view of both hemispheres of the planet.

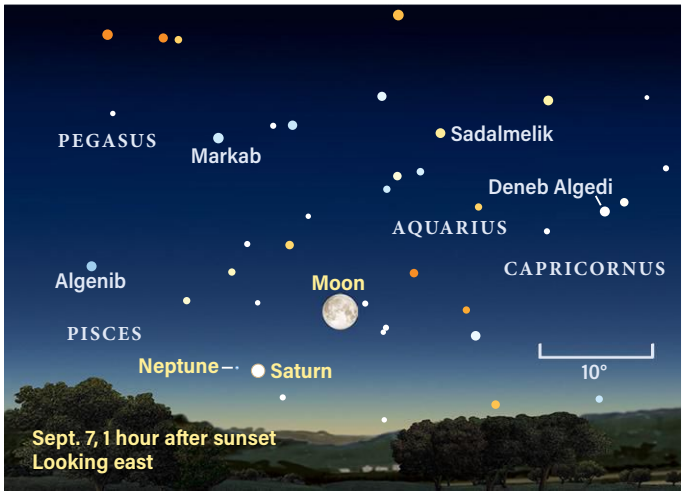
Five of Saturn's moons are relatively easy to track: Titan, Tethys, Dione, Rhea, and Iapetus. Titan is brightest (magnitude 8.5) and visible through any small telescope. It circles the ringed planet every 16 days.

We now see the major moons transit the face of Saturn. Most are too small to view easily, but Titan casts an obvious black dot on the disk, visible in most telescopes. There are two transits visible from the U.S. this month.

The first occurs Sept. 3/4 at 1 A.M. EDT (early on the 4th in the Eastern and Central time zones). It takes about 25 minutes for the full shadow to appear. You should notice a distinct notch forming at Saturn's northeastern limb by 1:12 A.M. EDT. Local conditions will affect how well you see ingress. Notice how far Titan is from the limb. We are still more than two weeks from opposition.

The shadow reaches the midpoint of the disk around 3 A.M. EDT; just under two hours later, Titan begins a transit across the northern polar region. The moon stands partially in front of Saturn's north

Full Moon leading



Saturn and Neptune sit close together all month. (Neptune will require optical aid to view.) In early September, the Full Moon joins them. ALL ILLUSTRATIONS: *ASTRONOMY*: ROEN KELLY

OBSERVING HIGHLIGHT

SATURN reaches opposition Sept. 21, two days before **NEPTUNE** follows suit.

pole at 5 A.M. EDT, shortly after its shadow began its egress.

The shadow is fully gone by 5:15 A.M. EDT and Titan's transit ends by 5:30 A.M. EDT. (Planetary imagers, note that Tethys and its shadow transit between about 4:30 A.M. EDT and 6:25 A.M. CDT, with the transit ending in twilight across the Midwest. The tiny shadow is unlikely to be visible through most telescopes.)

A second Titan transit occurs Sept. 19/20, just one day from opposition. Now Titan and its shadow almost overlap! Titan's transit begins at the northwestern limb of Saturn at 12:33 A.M. EDT. The shadow's ingress begins about two minutes later, although it will be difficult to tell them apart due to atmospheric conditions blurring the view. The dark notch of the shadow should be visible by 12:45 A.M. EDT. Titan is fully on Saturn's disk by 1:02 A.M. EDT.

Titan and its shadow, just arcseconds apart, travel across the northern polar region of Saturn. They're midway around 2:30 A.M. EDT. The shadow reaches the northwestern limb of Saturn just before 3:30 A.M. EDT and leaves by 4:05 A.M. EDT Titan remains fully on the disk another three to four minutes and exits fully by 4:37 A.M. EDT.

Titan is also occulted by Saturn. Late on Sept. 11, Titan enters Saturn's shadow just beyond the southwestern limb.

— Continued on page 34

RISING MOON | The Maginus sunrise ray

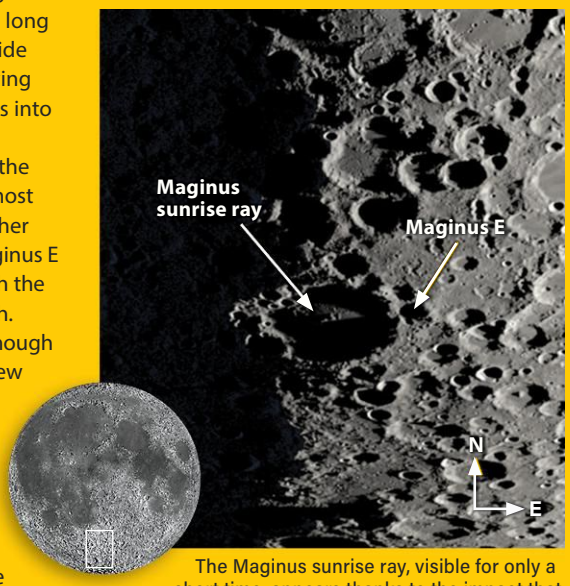
AS IF PIERCING A CRATER WALL, the rising Sun first lights up the central peaks of Maginus. Within 60 minutes, the light spreads into a long and narrow torch splitting the 100-mile-wide bowl into two dark halves. Over the following two hours, the Maginus sunrise ray spreads into a wider triangular beam.

The First Quarter Moon on Sept. 29 has the specific orientation to show off the ray to most of North America. If it is cloudy, give it another try on Nov. 27. The impact that created Maginus E to the east was big enough to blow through the wall, which lets the rising Sun shine through. You'd think this story would be common enough across the Moon's face, but there are very few hits that are both large enough and facing due east.

The unwrapping of this gift is so gradual that there's time to take your viewing party on a tour up the terminator. Is the sky steady enough to see the rille in the Alpine Valley? Get back to Maginus to note any change, then soak in the toothy black shadows cast into Archimedes. After another examination of the sunrise ray, jump to Plato, then have a final look at the cone of light on the crater floor before the Moon gets too low.

Maginus is named for Giovanni Antonio Magini, Italian mathematician and astrologer. He died in 1617 — might he have looked through Galileo's telescope before then?

Maginus



The Maginus sunrise ray, visible for only a short time, appears thanks to the impact that created Maginus E. NASA'S SCIENTIFIC VISUALIZATION STUDIO. INSET: NASA/GSFC/ASU

METEOR WATCH | Looking for light in the lull

The zodiacal light shines

The zodiacal light appears at left, angled upward from the horizon as the winter sky rises. ALAN DYER

NO MAJOR METEOR SHOWERS are active in September, so we enter a bit of a lull after the excitement of August.

Meteoritic dust from thousands of comets passing over the eons is visible before dawn as the zodiacal light, as sunlight reflecting off the dust creates a faint glow. You'll need a very dark eastern horizon with no streetlights nearby; higher elevations get a better view, too.

The zodiacal light appears as a faint cone-shaped glow aligned with the ecliptic. On September mornings well before dawn, the high angle of the ecliptic benefits views of it. The broad base of the glow is in Leo as that constellation rises, and narrows higher in the sky through Cancer and Gemini. Catch it on moonless nights in the third and fourth week of September for the darkest skies.

STAR DOME

HOW TO USE THIS MAP

This map portrays the sky as seen near 35° north latitude. Located inside the border are the cardinal directions and their intermediate points. To find stars, hold the map overhead and orient it so one of the labels matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

The all-sky map shows how the sky looks at:

10 P.M. September 1
9 P.M. September 15
8 P.M. September 30

Planets are shown at midmonth

MAP SYMBOLS

- Open cluster
- Globular cluster
- Diffuse nebula
- Planetary nebula
- Galaxy

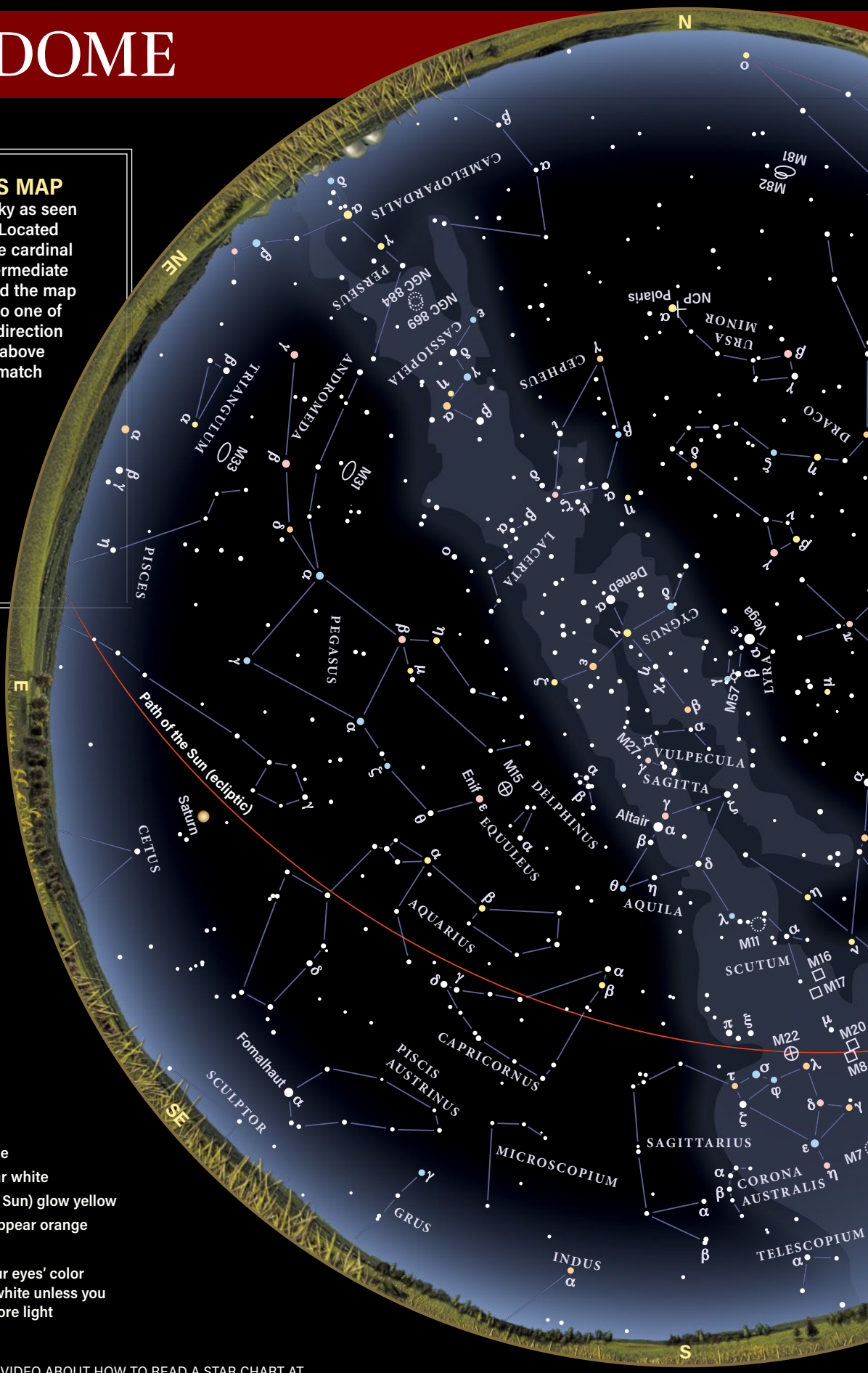
STAR MAGNITUDES

- Sirius
- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

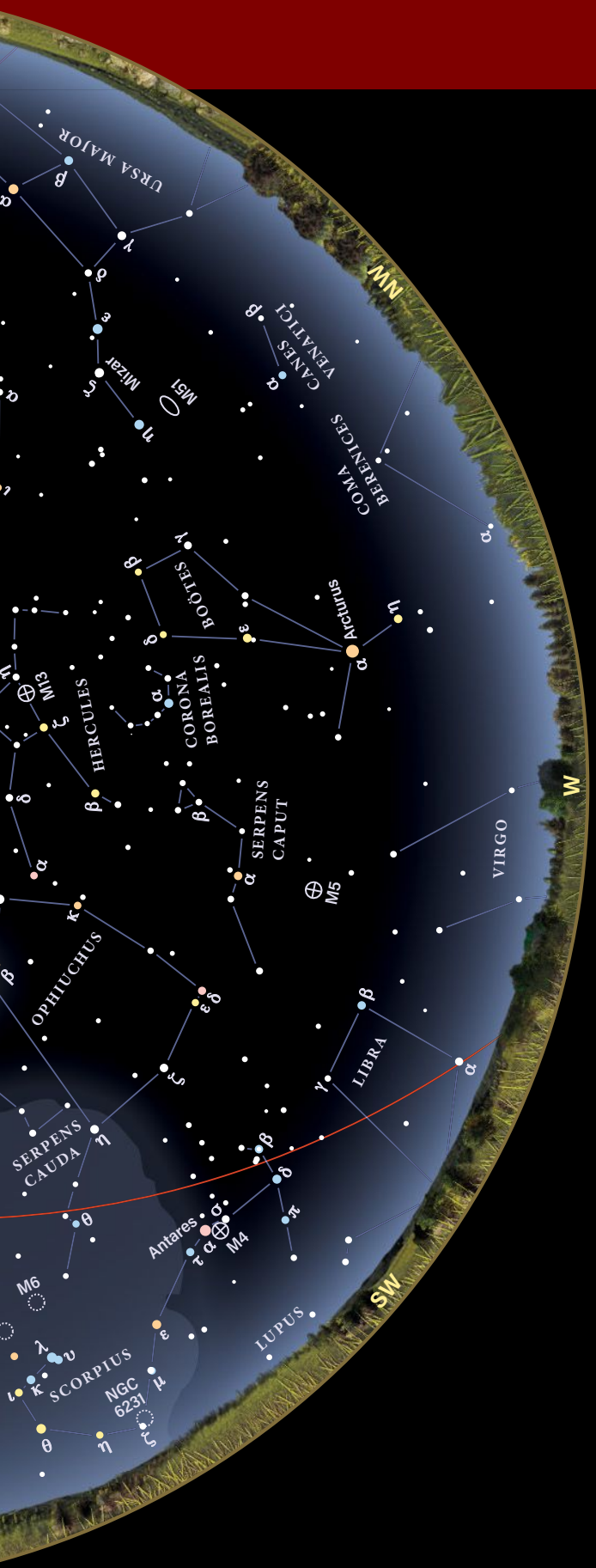
STAR COLORS

A star's color depends on its surface temperature.

- The hottest stars shine blue
- Slightly cooler stars appear white
- Intermediate stars (like the Sun) glow yellow
- Lower-temperature stars appear orange
- The coolest stars glow red
- Fainter stars can't excite our eyes' color receptors, so they appear white unless you use optical aid to gather more light



BEGINNERS: WATCH A VIDEO ABOUT HOW TO READ A STAR CHART AT **www.Astronomy.com/starchart.**



SEPTEMBER 2025

SUN.	MON.	TUES.	WED.	THURS.	FRI.	SAT.
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30				

ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

Note: Moon phases in the calendar vary in size due to the distance from Earth and are shown at 0h Universal Time.

CALENDAR OF EVENTS

2 Mercury passes 1.2° north of Regulus, 6 A.M. EDT

4 The Moon passes 0.06° south of Pluto, 10 A.M. EDT

6 Uranus is stationary, 1 A.M. EDT

7 Full Moon occurs at 2:09 P.M. EDT; total lunar eclipse

8 The Moon passes 4° north of Saturn, 4 P.M. EDT

The Moon passes 3° north of Neptune, 6 P.M. EDT

10 The Moon is at perigee (226,662 miles from Earth), 8:10 A.M. EDT

12 Mars passes 2° north of Spica, 4 A.M. EDT

The Moon passes 5° north of Uranus, 10 P.M. EDT

13 Mercury is in superior conjunction, 7 A.M. EDT

14 Last Quarter Moon occurs at 6:33 A.M. EDT

16 The Moon passes 5° north of Jupiter, 7 A.M. EDT

19 The Moon passes 0.8° north of Venus, 8 A.M. EDT

The Moon passes 1.3° north of Regulus, 8 A.M. EDT

Venus passes 0.5° north of Regulus, 9 A.M. EDT

21 Saturn is at opposition, 2 A.M. EDT

New Moon occurs at 3:54 P.M. EDT; partial solar eclipse

22 Autumnal equinox occurs at 2:19 P.M. EDT

23 Neptune is at opposition, 9 A.M. EDT

The Moon passes 1.1° south of Spica, 6 P.M. EDT

24 The Moon passes 4° south of Mars, 11 A.M. EDT

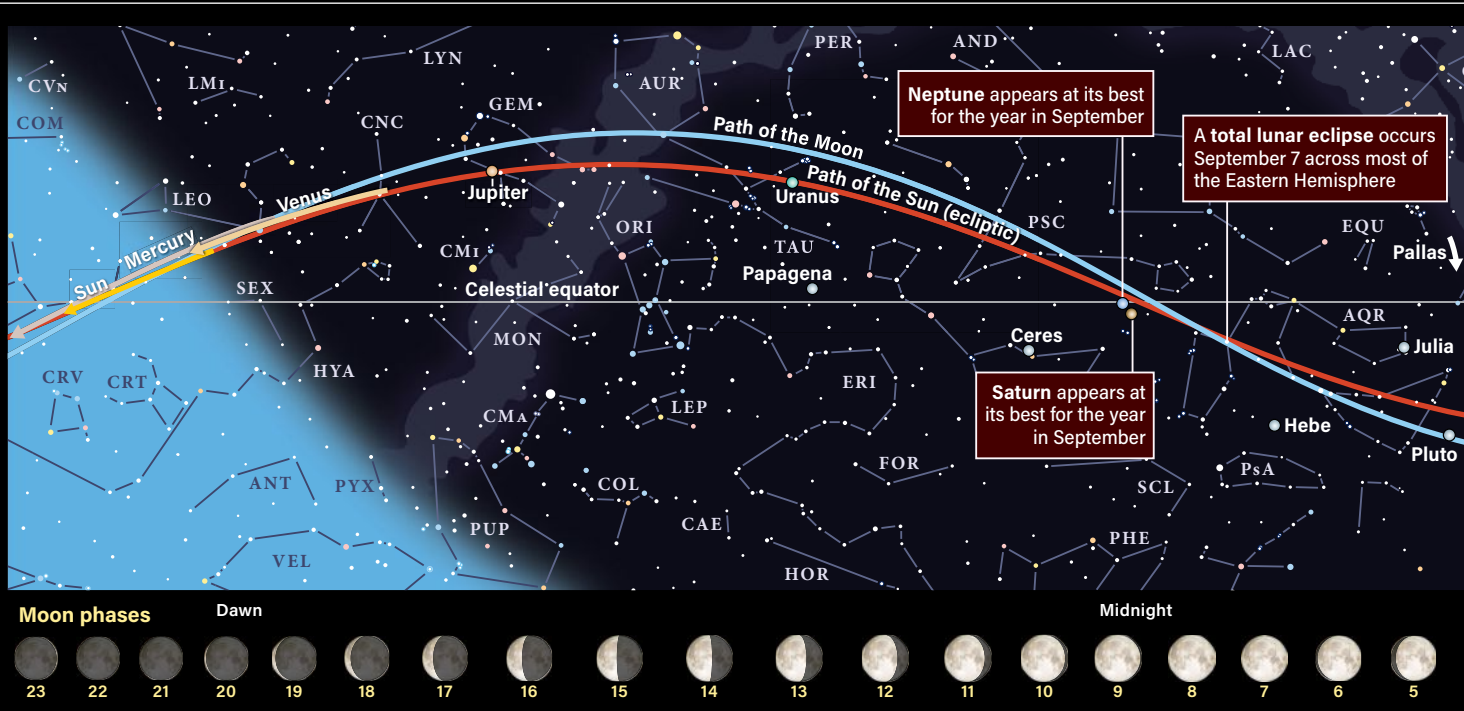
25 Asteroid Pallas is stationary, 7 A.M. EDT

26 The Moon is at apogee (251,996 miles from Earth), 5:46 A.M. EDT

27 The Moon passes 0.6° south of Antares, 2 P.M. EDT

29 First Quarter Moon occurs at 7:54 P.M. EDT

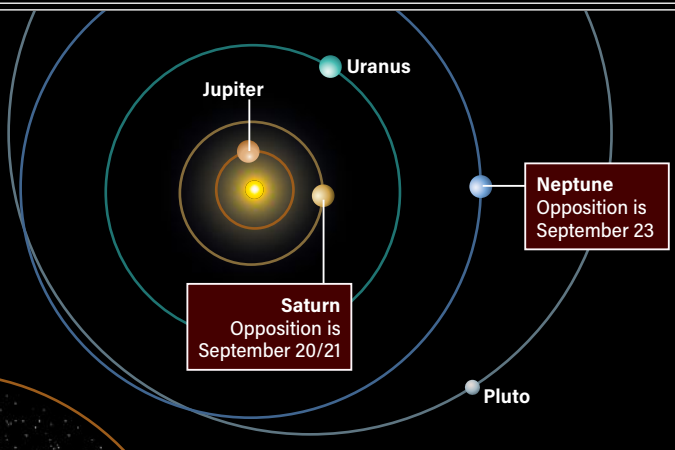
PATHS OF THE PLANETS

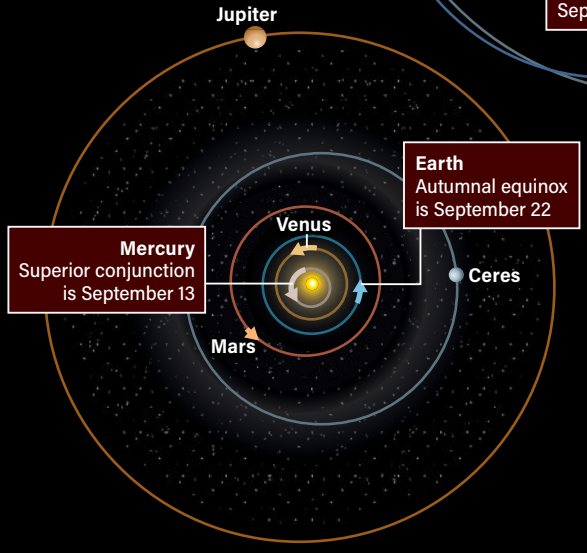


To locate the Moon in the sky, draw a line from the phase shown for the day straight up to the curved blue line.

THE PLANETS IN THEIR ORBITS

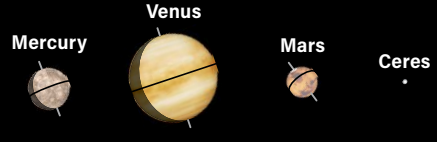
Arrows show the inner planets' monthly motions and dots depict the outer planets' positions at midmonth from high above their orbits.





THE PLANETS IN THE SKY

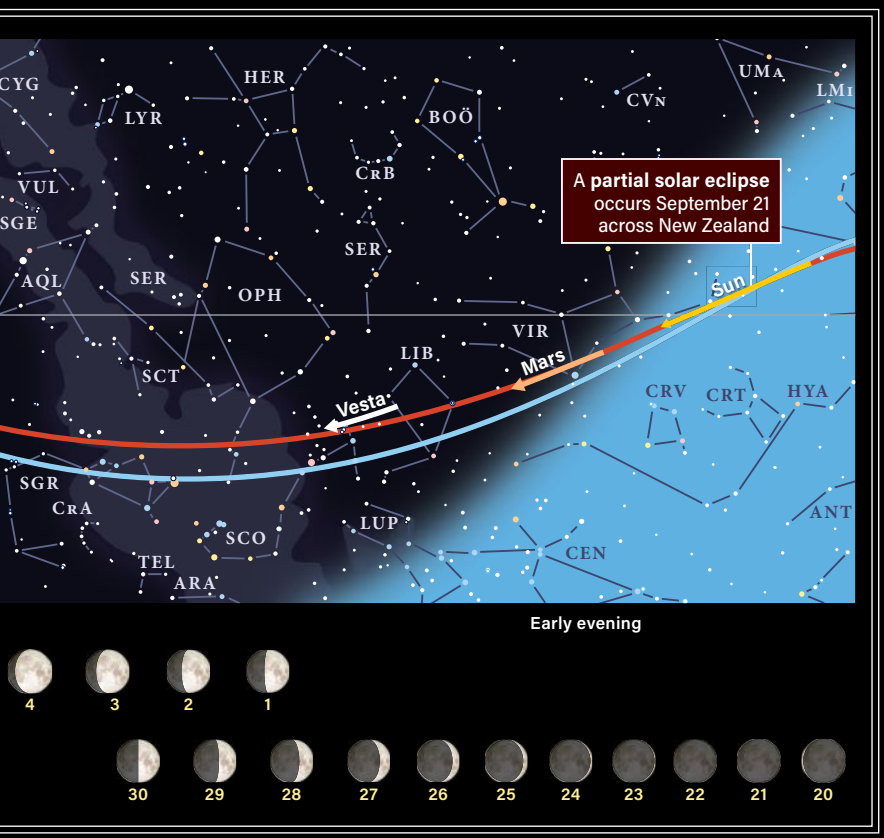
These illustrations show the size, phase, and orientation of each planet and the two brightest dwarf planets at 0h UT for the dates in the data table at bottom. South is at the top to match the view through a telescope.



PLANETS	MERCURY	VENUS
Date	Sept. 1	Sept. 15
Magnitude	–1.3	–3.9
Angular size	5.5"	11.7"
Illumination	87%	88%
Distance (AU) from Earth	1.223	1.432
Distance (AU) from Sun	0.314	0.719
Right ascension (2000.0)	9h57.8m	9h46.8m
Declination (2000.0)	14°02'	14°12'

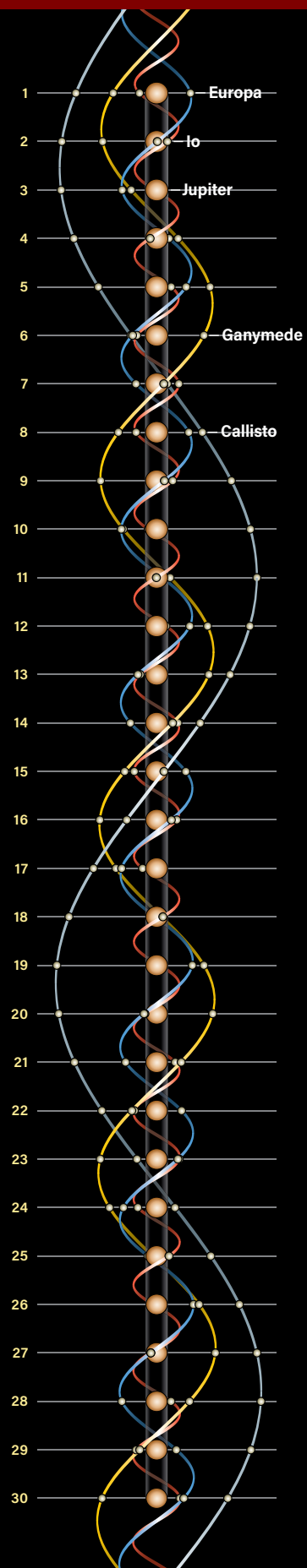
This map unfolds the entire night sky from sunset (at right) until sunrise (at left). Arrows and colored dots show motions and locations of solar system objects during the month.

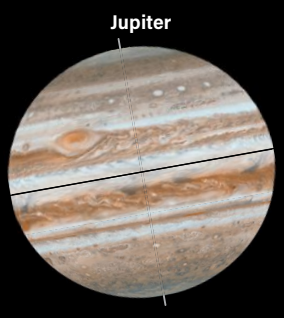
SEPTEMBER 2025

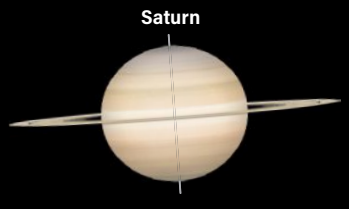


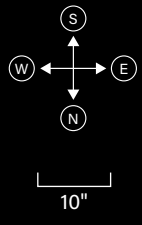
JUPITER'S MOONS

Dots display positions of Galilean satellites at 5 A.M. EDT on the date shown. South is at the top to match the view through a telescope.





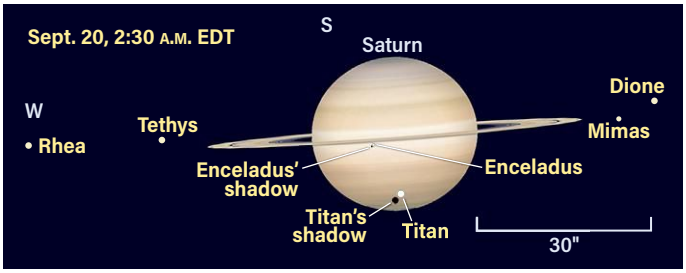




MARS	CERES	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
Sept. 15	Sept. 15	Sept. 15	Sept. 15	Sept. 15	Sept. 15	Sept. 15
1.6	7.8	–2.0	0.6	5.7	7.7	15.2
4.1"	0.7"	35.4"	19.4"	3.7"	2.4"	0.1"
97%	99%	99%	100%	100%	100%	100%
2.312	2.008	5.565	8.553	19.126	28.893	34.705
1.563	2.947	5.173	9.552	19.509	29.888	35.347
13h31.8m	1h11.4m	7h26.0m	23h58.9m	3h55.9m	0h04.5m	20h17.3m
–9°30'	–8°45'	21°57'	–2°51'	20°10'	–1°01'	–23°35'

 — Continued from page 29

Traveling together



One day before opposition, Titan and its shadow transit Saturn nearly simultaneously. Enceladus and its shadow are also transiting, but they will likely be too small and faint to pick up.

Watch closely as it begins fading at about 11:10 P.M. EDT; it's midway into the eclipse seven minutes later. The moon has disappeared by 11:33 P.M. EDT. Between 3:30 A.M. and 4:05 A.M. EDT on the 12th, Titan reappears from behind the southeastern limb.

Spot Titan again disappearing at the southwestern limb of Saturn Sept. 27, starting soon after 9:30 P.M. EDT (not visible in the Pacific time zone). The moon's reappearance at the southeastern limb begins around 2:07 A.M. EDT (now the 28th for some) and it is clear of the limb 27 minutes later.

Tenth-magnitude Tethys and Dione cross Saturn's disk the morning of opposition, Sept. 21. Dione leads around 4:03 A.M. EDT; Tethys follows less than five minutes later. Around 5:30 A.M. EDT, both moons lie roughly in the middle of the disk, just north of the rings.

On Sept. 1, Iapetus is two days past its brighter western elongation, 9' west of Saturn. Iapteus then fades to 11th magnitude as it approaches superior conjunction on the 18th, when it is only 1.3' due south of the planet. By Sept. 30, Iapetus reaches 8' east of Saturn and is nearing 12th magnitude.

Neptune remains together with Saturn within the field of view of binoculars, starting September 1.7° northeast of the ringed planet and ending the month 3° away. Saturn's motion causes the change — Neptune is so far that its own retrograde motion is barely perceptible.

Neptune shines at magnitude 7.7 and reaches opposition on the 23rd, two days after Saturn. On the 9th, the bluish planet stands a Moon's width south of a 6th-magnitude field star. It should be easy to spot. Simply center Saturn in a pair of binoculars, move northeast about half a field, and Neptune will be near the center of your view.

Uranus rises about an hour before midnight on Sept. 1 and is roughly 4.5° south-southeast of the Pleiades (M45). It reaches a stationary point Sept. 6 and moves westward the rest of the month. It shines at magnitude 5.7, an easy binocular object.

Uranus forms the base of a triangle together with 4th-magnitude 37 Tauri, which stands 3° northeast of Uranus and 4.5° southeast of M45 (the triangle's apex). The 4"-wide planetary disk is visible through a telescope. By the end of September, Uranus rises around 9 P.M. local daylight time and is 30° high in the east at midnight.

Jupiter is up in the east by 3 A.M. local daylight time on Sept. 1. Its northern declination affects rising times significantly, depending on your latitude. It's visible a few hours earlier by the end of September.

Jupiter dominates the constellation Gemini at magnitude –2.0. Atmospheric details are obvious through a telescope. Its disk spans 34", growing to 37" during the month.

Three of the Galilean moons — Io, Europa, and Ganymede — orbit in a 4:2:1 resonance. This causes simultaneous

WHEN TO VIEW THE PLANETS

EVENING SKY
Mars (west)
Saturn (east)
Neptune (east)

MIDNIGHT
Saturn (south)
Uranus (east)
Neptune (south)

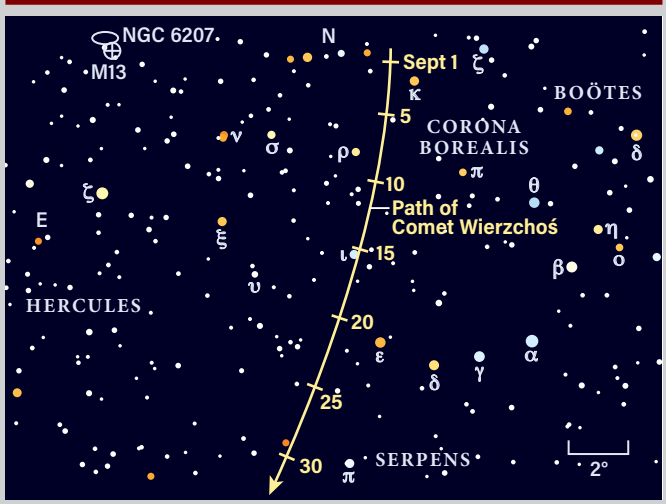
MORNING SKY
Mercury (east)
Venus (east)
Jupiter (east)
Saturn (west)
Uranus (south)
Neptune (west)

COMET SEARCH | Brightening prospects

C/2024 E1 WIERZCHOŚ ends the months of drought, chaseable with an 8-inch scope as long as you're out under dark country skies. There's no evening rush because it floats high to the west in Corona Borealis.

The easiest nights to find Wierzchoś are the 15th and 16th, when it lies half a degree from Iota (ι) Coronae Borealis, the last (easternmost) jewel in the Northern Crown. Dropping inside the orbits of main-belt asteroids, the small comet is just waking up, its coma of dust only a couple arcminutes across and barely out of round, mimicking an elliptical galaxy. Use 150x or more to study its shape and compare it to the spiral galaxy NGC 6207, which flanks M13.

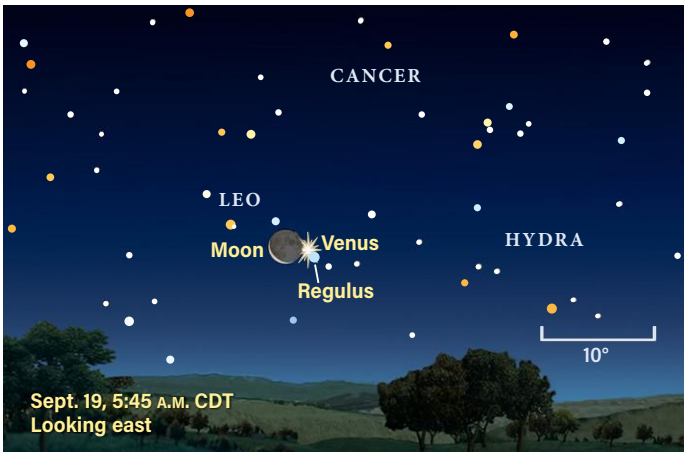
Comet C/2024 E1 Wierzchoś



Comet Wierzchoś slides near the Northern Crown this month, closely approaching Iota CrB midmonth.

This classic Oort Cloud object was picked up by Kacper Wierzchoś working at Arizona's Mount Lemmon. Newsfeeds may be touting a light-up-the-sky naked-eye show for January, but it will be a modest 4th-magnitude peak favoring observers south of the equator.

Stand in line



Venus, the Moon, and Regulus line up Sept. 19 for a stunning morning spectacle. This chart shows the sky an hour before sunrise from 40° north and 90° west. Your view will differ depending on your location.

transits to repeat. The action begins Sept. 20 as Io and Europa transit, underway as Jupiter rises along the East Coast. The low altitude makes observation difficult. Seven days later, on Sept. 27, Io and Europa again cross the disk with their shadows as the planet rises. By 12:59 A.M. EDT, Io's shadow is noticeable on the eastern limb, with Europa's shadow near the western limb. Twenty-five minutes later, Europa begins its transit. Europa's shadow leaves the disk at 1:40 A.M. EDT.

Io begins to transit at 2:09 A.M. EDT; its shadow leaves the disk 61 minutes later. Europa's transit ends at 4:14 A.M. EDT, and Io follows nine minutes later. But it's not over yet: Io catches up with Europa and passes partially behind it between about 4:49 A.M. and 5:09 A.M. EDT.

Ganymede's shadow is transiting Sept. 7 as Jupiter rises in the Midwest. The shadow leaves Jupiter beginning at 5:33 A.M. EDT and takes about 10 minutes to exit. Ganymede itself is near the southeastern limb, reaching it at 5:55 A.M. CDT. West Coast observers will see Ganymede in the middle of the disk roughly an hour before sunrise.

Io and its shadow transit Sept. 18 after Ganymede reappears from occultation (egress at 4:17 A.M. EDT is visible from the Eastern and Central time zones). Io's shadow appears at 4:34 A.M. EDT and Io itself begins a transit at 5:44 A.M. EDT.

Venus rises just before 4 A.M. local daylight time Sept. 1, shining at magnitude –3.9. Rising more than 2.6 hours before the Sun, Venus is visible in the eastern sky. It stands some 20° high at 6 A.M. local daylight time.

Don't miss the binocular view on this morning with the Beehive star cluster (M44) just 1° north of the planet. It's also stunning in a low-power scope.

On this day, Venus displays a 84-percent-lit disk 12" wide. By the end of September, the phase has expanded to 91 percent and the disk shrunk to 11", owing to increasing distance from Earth.

Venus moves east into Leo by Sept. 10 and reaches a wonderful event Sept. 19, when the brilliant planet stands one Moon's width due north of Regulus.

The waning crescent Moon is also very close; its position depends on your time zone and latitude. Observers in the northeastern U.S. see the Moon about 1° northwest of Venus at 4:30 A.M. EDT, moving to a position about 0.5° due north of Venus just before sunrise. Venus is occulted by the Moon from Northern Canada, Greenland, Iceland, and Europe.

Kansas City sees the Moon, Venus, and Regulus in a straight line shortly after rising, the Moon still 0.5° north of Venus. Within an hour, the Moon moves northeast of the planet. As the trio rises farther west, the Moon stands a greater distance northeast of Venus.

Mercury is a challenge, rising an hour before the Sun on Sept. 1. It shines at magnitude –1.3 and stands 2.5° northwest of Regulus, also challenging in twilight. On the 2nd, Mercury is 1.2° due north of Regulus. The planet quickly drops out of view and reaches superior conjunction with the Sun on the 13th. It will reappear low in the evening sky by October.

Martin Ratcliffe *is a planetarium professional with Evans & Sutherland and enjoys observing from Salt Lake City.* **Alister Ling**, *who lives in Edmonton, Alberta, is a longtime watcher of the skies.*

GET DAILY UPDATES ON YOUR NIGHT SKY AT **www.Astronomy.com/skythisweek.**

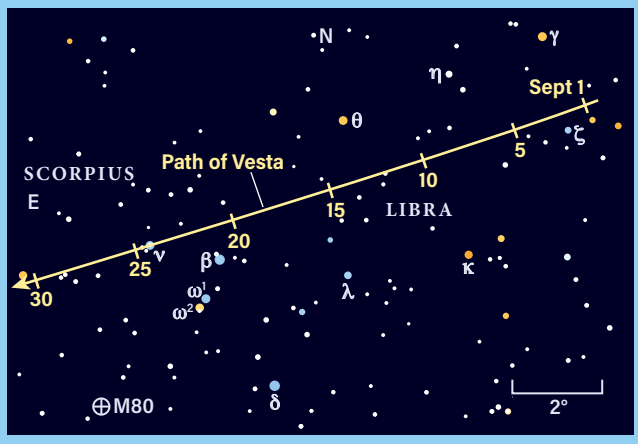
LOCATING ASTEROIDS
Past its peak but holding the torch

IT'S TIME to use a small scope to locate 4 Vesta. Slowly fading through magnitude 7.8, it also lies low in the southwestern sky, where its light will be attenuated by the longer path through our atmosphere. Don't wait for full darkness. Fortunately, it's a simple hop from ruby Antares up to the showcase double star Beta (β) Scorpii and a slide westward toward the lozenge-shaped quad of Zeta (ζ) Librae stars.

On the 12th, Vesta creates an optical double star with a slightly brighter companion only a couple of arcminutes away. Is the asteroid's light somewhat "flatter" than the star's? Egg-shaped Vesta is 330 miles across, appearing to us 0.3" wide — size of a star's Airy disk in a 12-inch scope.

The highlight of the month takes place on the 24th, when Vesta becomes the 5th component of Nu (ν) Scorpii. In 1905, Agnes Clerke called this star "perhaps the most beautiful quadruple system in the heavens."

Into the Scorpion's lair



Vesta enters Scorpius this month, making a stunning near pass of Nu Scorpii.

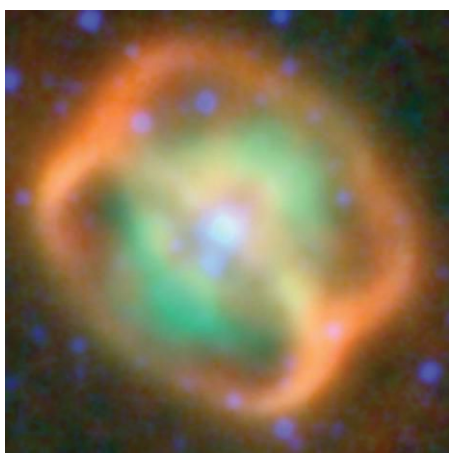
GAZING AT A CRYSTAL BALL

A tight-knit binary system sculpts intricate details in planetary nebula NGC 1514. BY RICHARD TALCOTT

A STAR LIKE THE SUN lives modestly for billions of years, converting the nuclear fuel in its core into energy that ultimately escapes as light and heat. But the most spectacular phase of a Sun-like star's existence lasts only tens of thousands of years and coincides with its death. The star puffs off its outer layers and forms a stunning planetary nebula of glowing gas and dust.

This fate awaits all stars that begin life with up to 8 solar masses. So far, astronomers have cataloged some 3,500 planetary nebulae in our galaxy. Most look best in visible light, but a few put on their best face when viewed at longer infrared wavelengths.

The Crystal Ball Nebula (NGC 1514) in Taurus makes perhaps the best case. At optical wavelengths, the nebula appears roughly spherical with several small bubbles. Infrared observations from 15 years ago revealed two dusty rings that encircle the visible nebula, which lies 1,500 light-years from Earth. And now the James Webb Space Telescope (JWST) has sharpened our view even further, resolving tangled patterns and clumpy knots in the rings.



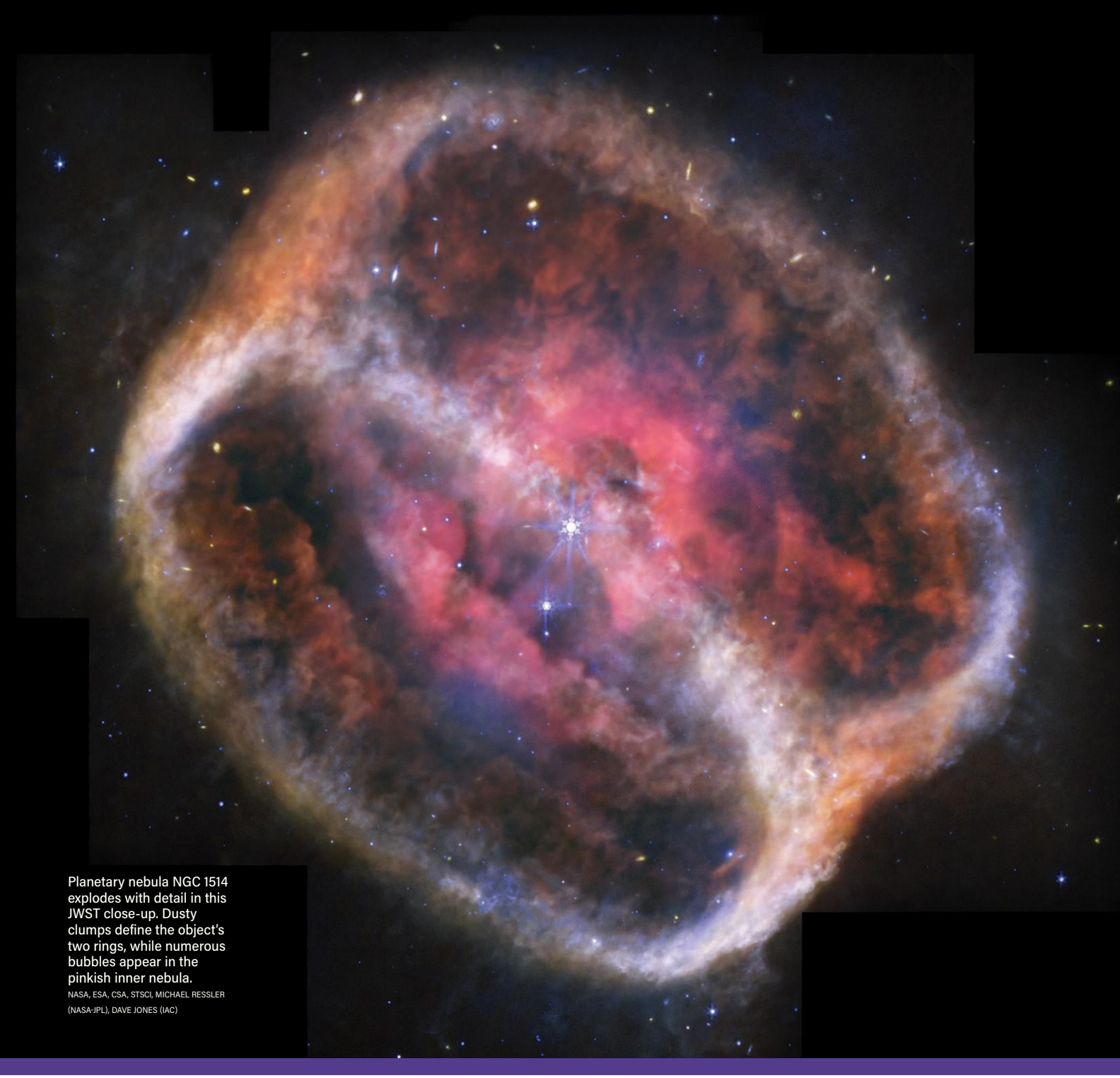
This WISE portrait of NGC 1514 from 2010 revealed two smooth orange rings surrounding an amorphous green inner nebula. NASA/JPL-CALTECH/UCLA/MICHAEL RESSLER (NASA-JPL)

AN EXQUISITE VISTA

"Before Webb, we weren't able to detect most of this material, let alone observe it so clearly," said Mike Ressler, project scientist for JWST's Mid-Infrared Instrument (MIRI), in a press release. Ressler, a researcher at NASA's Jet Propulsion Laboratory in Pasadena, California, discovered the rings in 2010 in an image taken with NASA's Wide-Field Infrared Survey Explorer (WISE). "With MIRI's data, we can now comprehensively examine the turbulent nature of this nebula," he said.

JWST reveals NGC 1514's hourglass shape, dusty clumps throughout the rings, and a bright pink core — the only region visible at optical wavelengths — riddled with distinct voids. Sitting at the nebula's center is a 9th-magnitude binary system. Its two stars follow a tight, elongated orbit that takes nine years to complete, and reside close enough to each other that even JWST can't separate them. The slightly fainter star to the binary's lower left lies in the foreground.

The binary system has been sculpting the nebula for at least the past 4,000 years. The primary star began life with several times the Sun's mass. "As it evolved, it puffed up, throwing off layers of gas and dust in a slow, dense stellar wind," said David Jones, a senior scientist



Planetary nebula NGC 1514 explodes with detail in this JWST close-up. Dusty clumps define the object's two rings, while numerous bubbles appear in the pinkish inner nebula.
NASA, ESA, CSA, STSCI, MICHAEL RESSLER (NASA-JPL), DAVE JONES (IAC)

at the Institute of Astrophysics of the Canary Islands and the person who confirmed the binary's existence in 2017. "When the primary star was shedding material, the companion likely got very close, influencing the shape of the ejected gas and dust."

A CLEAR VIEW

The primary's exposed core has become a super-hot white dwarf with a much faster stellar wind. The dwarf's ultraviolet radiation excites the surrounding gas and causes it to glow, while the high-speed wind punches holes in the inner nebula.

The two rings show lots of texture that WISE did not pick up. "We think the rings are primarily made up of very small dust grains," said Ressler. "When these grains are hit by ultraviolet light from the white dwarf star, they heat up ever so slightly, which makes them just warm enough to emit the mid-infrared light MIRI detects."

Surprisingly, spectra found no hint of the complex carbon molecules known as polycyclic aromatic hydrocarbons, which are common in other planetary nebulae. These smokelike compounds make many planetaries appear hazy; their absence in NGC 1514 helps make the JWST image so sharp.

Contributing Editor **Richard Talcott** *wrote about JWST's observations of the Phoenix galaxy cluster in the August issue.*

Take *time* with your images

These simple long-term photographic projects can show how celestial objects move and change.

TEXT AND IMAGES BY SOUMYADEEP MUKHERJEE

IMAGINE YOU'RE GOING down a long waterslide. You've been traveling through it enjoying every moment despite occasional bumps on the way. You know the end will eventually come, but you don't know when, where, and how it might feel.

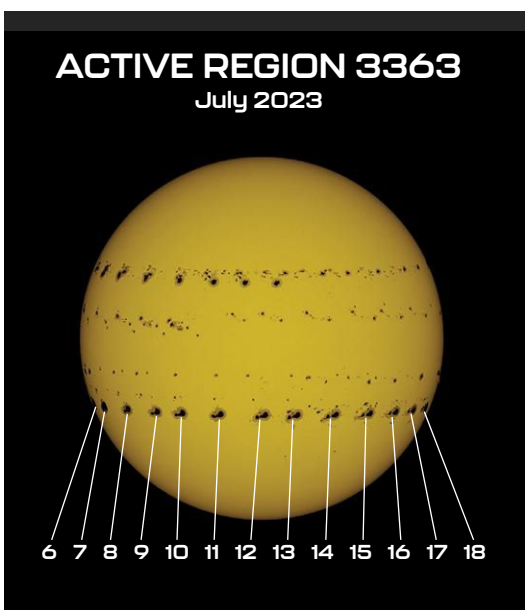
Long-term projects imaging celestial objects feel the same way: It's a long path down a known road, but you might not know what the final image will look like.

Documenting the sky has its charm, and doing so over time can make it even more fun. Some of the most popular options are recording solar and lunar analemmas or retrograde motions of planets. But I want to explore some less common projects that give you more freedom in terms of creating and composing the image. The most intriguing thing about these projects is that the resulting image is hard to predict. It's a journey and, as they say, "the journey is more beautiful than the destination."

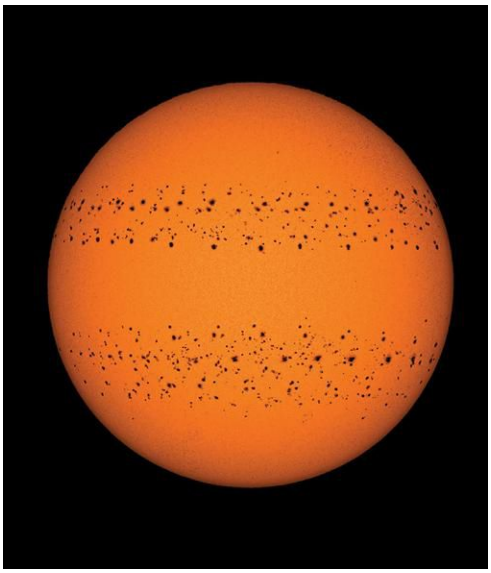
What is a long-term project?

Long-term astrophotography projects involve capturing a celestial object through time, showing its changing position and/or appearance in the sky. Such a project can last anywhere from a few days to a few years and

LEFT: One of the author's projects captured the phases of a complete lunar cycle in 2021. Because the New Moon can't be photographed, he used an underexposed version of the Full Moon. (Nikon D5600; Sigma 150-600c lens; Benro tripod; from Kolkata, India)



RIGHT: The movement of Active Region 3363 across the solar disk from July 6 to 18, 2023, is shown here. (Nikon D5600; Sigma 150-600c lens; Benro tripod; Thousand Oaks white light solar filter; from Kolkata, India)

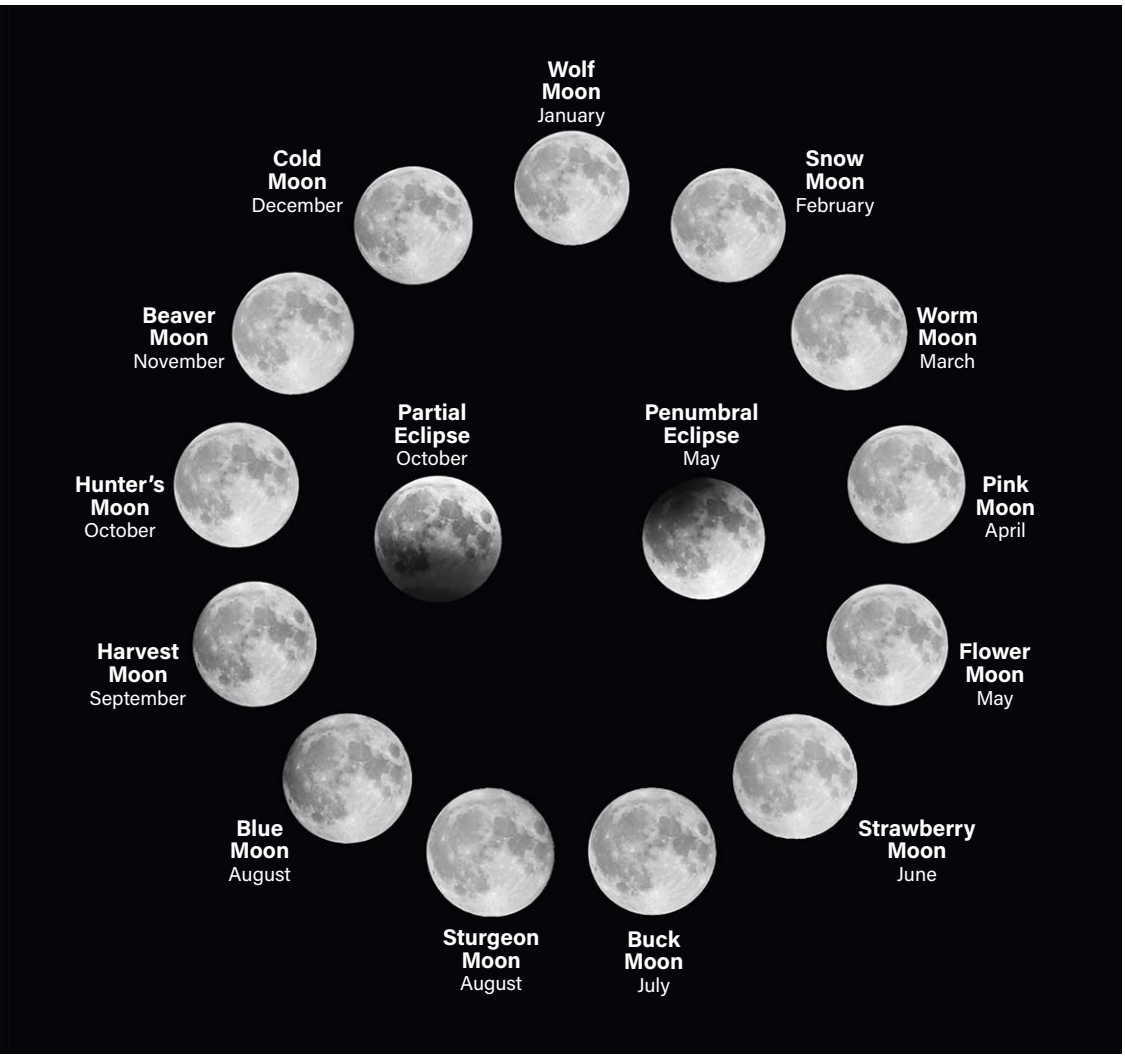


ABOVE, LEFT TO RIGHT: This composite shows all sunspots from Dec. 25, 2020, to Dec. 31, 2021. (Nikon D5600; Sigma 150-600c lens; Benro tripod; Thousand Oaks white light solar filter; from Kolkata, India)

Here are the four Super Moons from July to September 2023, arranged to look three-dimensional. (Nikon D5600; Sigma 150-600c lens; Benro tripod; from Kolkata, India)

This image presents a comparison between a Super Moon (at perigee) and a Micro Moon (at apogee) in May and December 2021. (Nikon D5600; Sigma 150-600c lens; Benro tripod; from Kolkata, India)

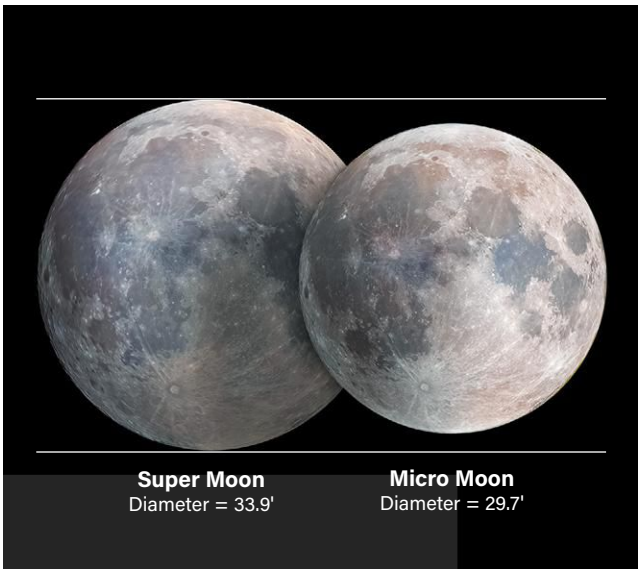
The author photographed 50 Full Moons between October 2020 and October 2024. The images are arranged in the shape of the Triple Moon Goddess symbol. The large Moon at the center is a strip-collage of all the Full Moons. (Nikon D5600; Sigma 150-600c lens; Benro tripod; from Kolkata, India)

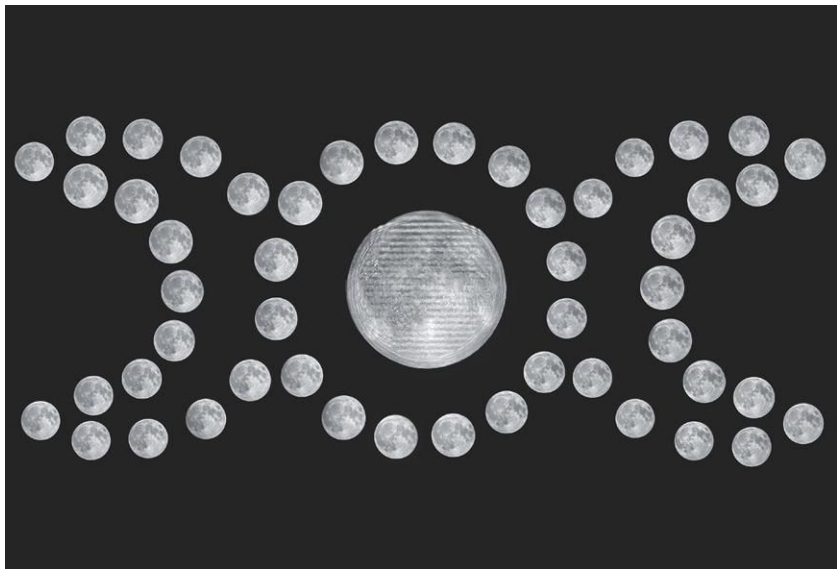


For this image, the author captured the 13 Full Moons of 2023, including a Blue Moon in August. In the middle, the center row shows a partial lunar eclipse (left) a penumbral lunar eclipse. (Nikon D5600; Sigma 150-600c lens; Benro tripod; from Kolkata, India)

may involve imaging the same object many times. It records both change and continuity.

Long-term projects are part of why astrophotography is considered a marriage of art and science. Creating the final image provides enough science to show fundamental properties of the subject, and





at the same time it gives the photographer an opportunity to unleash creativity in the way the final composition is wrought.

Prerequisites

Many long-term projects can be taken up by anybody with a camera, a lens, and a tripod (and some basic filters, if required). Depending on the subject, you might use a wide-angle lens (18mm to 50mm) or a telephoto lens (135mm to 600mm).

Apart from the equipment, an astrophotographer will need what I call "the six Ps" to initiate and complete a project. Three of these are technical: Planning (creating an outline for the project), Photographing (doing the actual shooting), and Processing (converting the raw data into a beautiful image). From a nontechnical standpoint, an astrophotographer will require three more: Passion (a love for the sky), Patience (the time to complete the work), and Perseverance (to keep up the required daily/weekly/monthly routine).

Projects with the Sun

Because the Sun is currently going through solar maximum, now is one of the best times to start a long-term project with it. It's easy to get started: Take an image of the Sun every day. The solar disk is dynamic, so you'll observe not only new sunspots but also existing spots changing shape and size as they move across the Sun's face. All you need is a DSLR camera, a telephoto lens, a solar filter, and a tripod.

You can start by tracking a single sunspot. Begin when it lies at one edge of the solar disk, and end when the sunspot vanishes at the other edge. This typically takes 12 to 15 days.

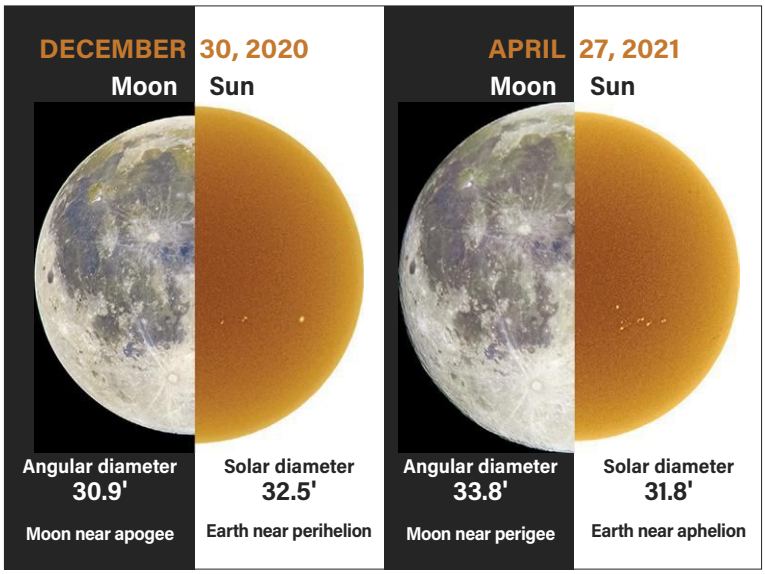
A solar project, however, can run for months or years. There's no strict endpoint. Taking images of the Sun every day will not only give you a final image, but you'll also have the option to create multiple images over the course of the project. These can allow a comparison of sunspots between weeks, months, or even quarters. You also can create an image with a specific number of days: 100, 200, or 300. If your dates happen to encompass Earth's perihelion (the first week of January) and aphelion (the first week of July), you can produce a collage comparing the different apparent sizes of the solar disk.

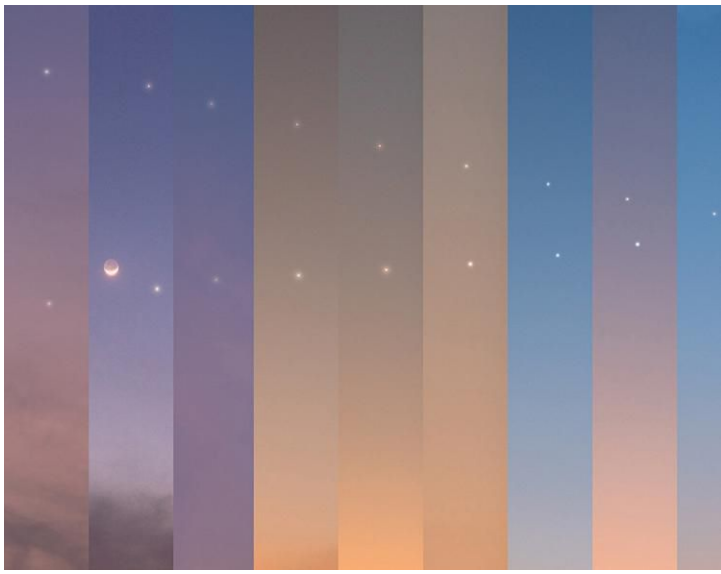
Planning for a solar project mainly involves when to begin. You don't have to decide when to end until later. Pick a start date when there is a maximum chance of clear skies. (E.g., monsoons are not the best time to begin a project.) However, if you continue taking images for many months, you'll eventually encounter seasonal weather changes, such as increased cloudiness or storms. All you need to do is go outside and take an image of the Sun every day; it doesn't need to be at the same time. These daily images can be single or comprise a stack of multiple images. The decision lies with you, but committing to multiple image stacks will require more time, both for photographing and processing.

During processing, arrange the solar disks linearly. You'll also need to rotate the images to counter the field rotation introduced on consecutive days. As a reference point, you can use images from NASA's Solar Dynamics Observatory directly from its website (http://sdo.gsfc.nasa.gov). To create a composite image with data from multiple days, load all the images into Photoshop (or a similar program) as layers and choose the blend mode "Darken" for all of them.

Projects with the Moon

While the Sun's changing nature is seen as sunspots and other surface features through specialized equipment, the Moon shows us naked-eye changes. Long-term projects with our satellite can capture the different phases, its libration, changes in apparent size, and more. For a monthlong project, you can start with capturing the Moon every night. The final image will show all the phases, from New Moon to the next New Moon. The key is to choose a month with the clearest possible skies. The final image will give you a lot of liberty



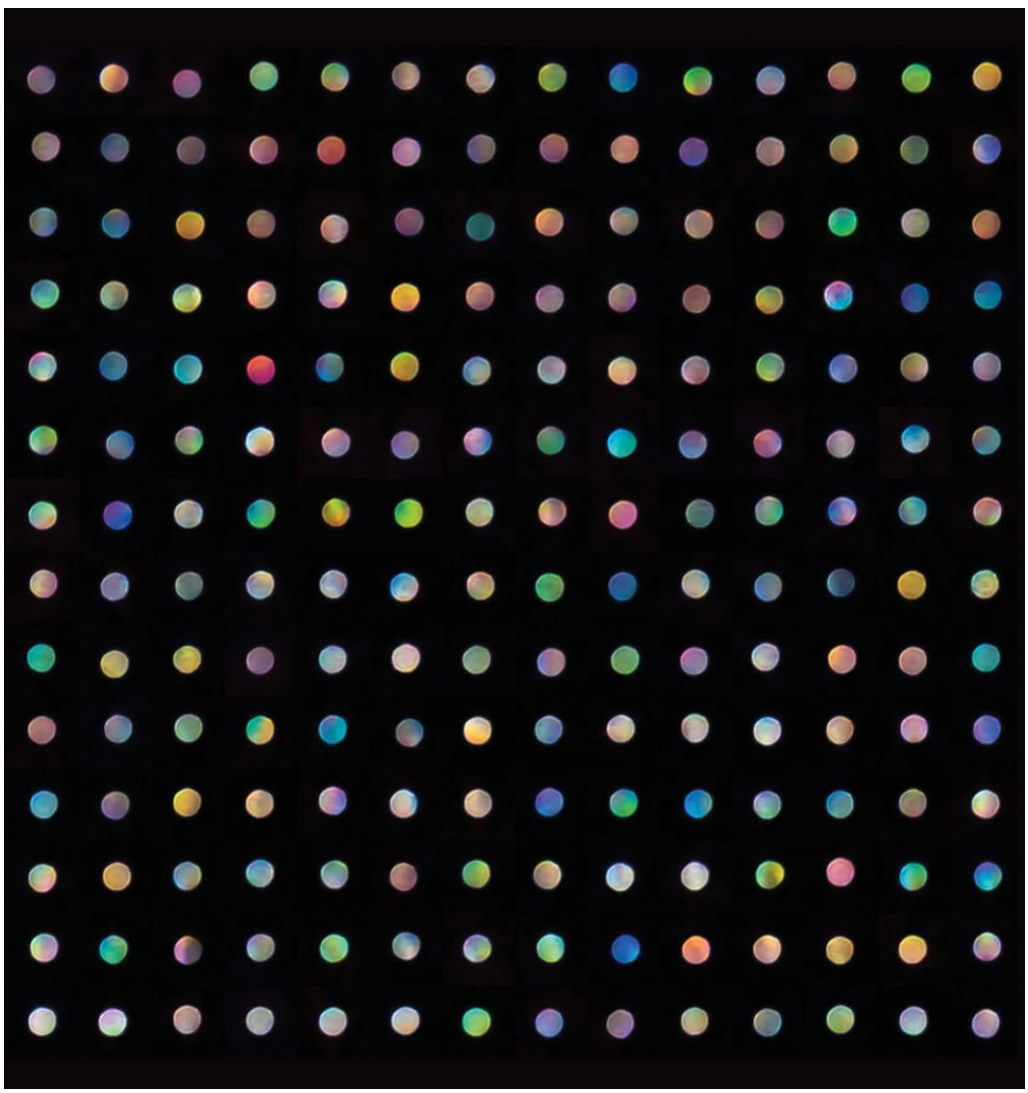


ABOVE, LEFT TO RIGHT: This image compares the apparent sizes of the Sun and the Moon at their nearest and farthest from Earth. (Nikon D5600; Sigma 150-600c lens; Benro tripod; from Kolkata, India)

Ten days of photos showing the apparent movements of Jupiter (top) and Venus are combined in this image. The author captured them during twilight, starting 10 days before their conjunction. (Nikon D5600; Sigma 150-600c lens; Benro tripod; from Dhanbad, India)

The photos in this collage were captured over three days. It shows the journey of Venus from sunset to astronomical night. As twilight progresses, the background stars and the Milky Way become gradually visible. (Nikon Z8 and Nikon Z6iii cameras; Nikon Z 14-24mm and Nikon Z 20mm lenses; Leofoto and Benro tripod; from Singalila National Park, India)

Captured over an hour, this image shows the appearance of a crescent Moon from sunset to astronomical twilight. Note how earthshine becomes gradually visible. (Nikon D5600; Sigma 150-600c lens; Leofoto tripod; from Kolkata, India)



The image combines 196 photographs of Sirius (Alpha [α] Canis Majoris) as it twinkled because of Earth's atmosphere. (Nikon D5600; Sigma 150-600c lens; Benro tripod; from Kolkata, India)

in terms of composition. Just choose what you prefer most.

A longer, less demanding project would photographing Full Moons every month. This requires only one night of effort per month, plus you'll get plenty of time to plan each image and to revisit if required.

This project will take 12 months, rendering a year of Full Moons. With the collected data, multiple images can be created, including a collage of all 12 Full Moons, a collection of only the Super Moons that appeared during the year (if there are any), or a comparison of the apparent sizes of the Full Moon during perigee and apogee.

The project can be started any month, though beginning at the start of the calendar year can be quite satisfying. But don't stop there. You can continue for as long as you want. A collage of 50 or 100 Full Moons can look fantastic. With more data, you can create a short video showing the libration of the Moon.

Some projects can include both the Sun and the Moon. One could look at their apparent sizes on a specific date or during perigee/perihelion and apogee/aphelion.

A few "not so long" projects

If you're unsure whether you want to commit to a long-term project, start with a shorter one. For example, a weeklong project could include a nightly photograph of a special celestial event, like a conjunction of two planets. You can either start the project up to six days before and end on the day of the conjunction, or continue for another six days after it. This will capture the movement of the two planets as they move closer and then farther apart.

A much shorter project, only a few hours long, can be done with a bright planet like Venus or with a crescent Moon. Focus on these in the twilight period and capture the changing sky background. Start just before or at sunset when Venus or the Moon becomes visible. Then take an image during sunset, civil twilight, nautical twilight, astronomical twilight, and astronomical night. Such images of Venus in particular will slowly reveal the background stars as darkness falls, and are ideal if it's in or near a prominent region in the sky (like Sagittarius). If your target is the crescent Moon, you'll capture earthshine as well as the background stars.

You can pursue a shorter project still with bright stars like Sirius by aiming to capture the different apparent shades of the star as it twinkles. You'll need to take 100 or more exposures (there is no specific number) of the defocused star to create a collage.

A few tips

Now that you have an idea of some prospective projects, here are a few suggestions that will help make your experience smoother.

• Data arrangement is important. Sort your data every day (or every week) in folders and subfolders labeled with dates. Note anything special in a document, and keep it in that folder.

• Back up your data regularly, the more frequently (e.g., every day or every three days), the better. Put a copy of your raw data on an external device or online. You don't want to lose your hard-earned data to a technical fault on your computer.

• Experiment during photographing and processing with different subjects and projects. But in all cases, the final image should be yours.

• Be creative. The final image could end up close to what you imagined, but if you come up with ideas along the way that mean it might turn out differently, follow them.

• If you get stuck at any point or run out of ideas, discuss it with a fellow photographer and collaborate.

By now, I've given you several options for possible projects. If you already have the basic equipment, start planning. Just remember: These suggestions are just starting points. The sky is the limit — literally.

Soumyadeep Mukherjee *is an amateur astrophotographer, astrophotography educator, and writer from Kolkata, India.*

A GUIDE TO BEGINNER'S GUIDES

Before you head out for your first look at the sky, take a look at these books. TEXT AND IMAGES BY RAYMOND SHUBINSKI

AN INTEREST IN ASTRONOMY may strike early in life or later. Regardless of what lit the fire of that interest, you need knowledge to help you understand the universe. Some of the most important sources of information are the many beginner's guides on astronomy. No matter what form these guides may take, they provide the basic information needed to send the enthusiast on an exciting lifelong journey.

Personal history

I can't remember exactly when I became interested in astronomy, but I was young. My mother bought me my first astronomy guidebook when I was 8 years old. We were checking out at a dime store when I spotted a pocket-sized Golden Nature Guide called *Stars: A Guide to the Constellations, Sun, Moon, Planets, and other Features of the Heavens*. I'm embarrassed to say my mother finally took the book to the register and bought it for me to stop my begging. It was part of a pantheon of nature books published by the Golden Press, and it was developed and edited by Herbert S. Zim.

Astronomer Robert H. Baker wrote this little book, which was first published in 1951. Baker was already well-known for his previous publications, including *Introducing the*

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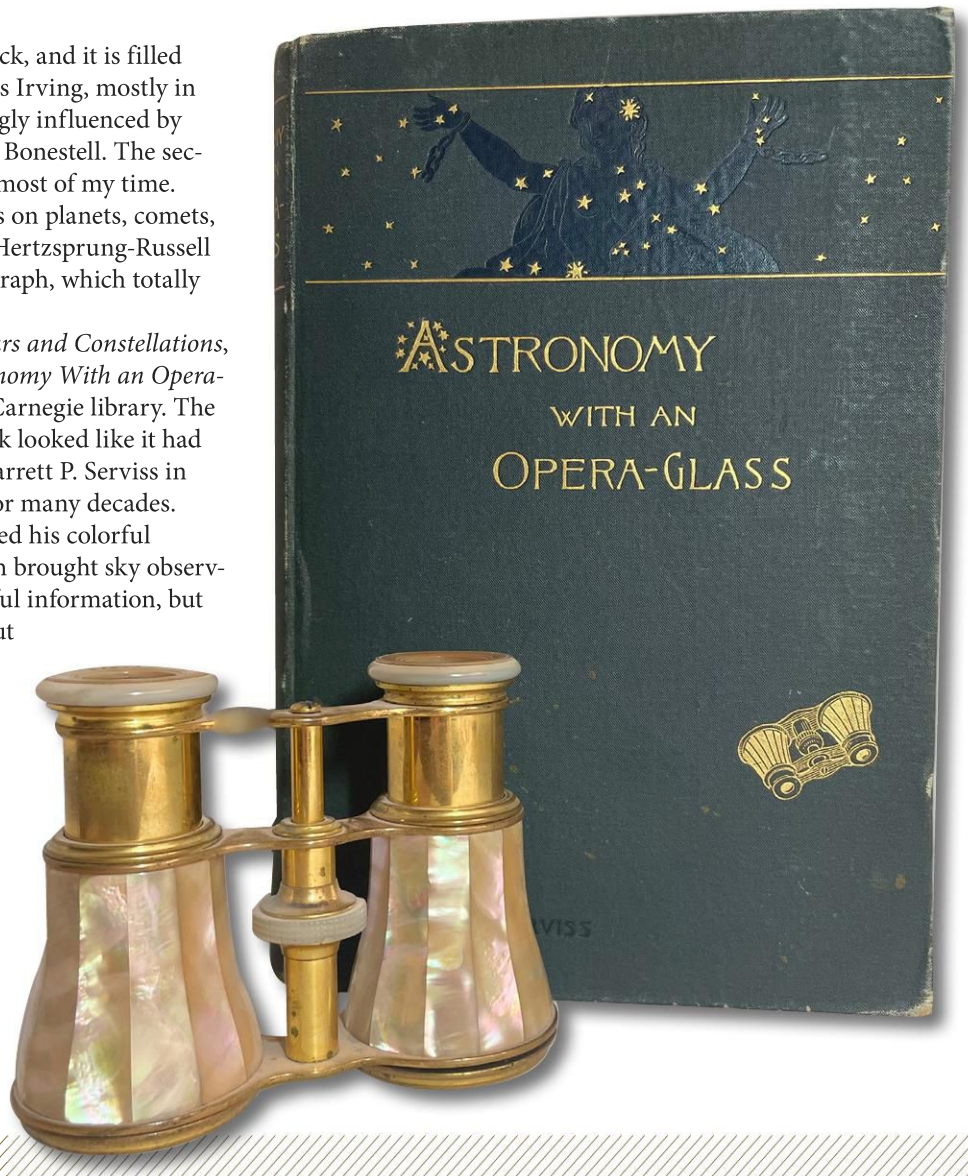
STARS
A GUIDE TO THE CONSTELLATIONS, SUN, MOON, PLANETS AND OTHER FEATURES OF THE HEAVENS
A GOLDEN NATURE GUIDE
The Observer's Book of
ASTRONOMY
PATRICK MOORE, F.R.A.S., F.R.S.A.
FIELD BOOK of the SKIES
WITH CHARTS, AND SPECIAL DIAGRAMS
by WILLIAM T. OLCOTT
REVISED AND EDITED BY R. NEWTON and MARGARET W. MAYALL
A clear and concise presentation of the main facts of modern astronomy, a brief story of the mythology of the constellations, and a practical field book for the observer of the stars, whether with naked eye, field glass, or telescope.
A PUTNAM NATURE FIELD BOOK

Constellations in 1937. My copy cost a buck, and it is filled with more than 150 illustrations by James Irving, mostly in color. The images in the book were strongly influenced by space artists Lucien Rudaux and Chesley Bonestell. The section on constellations was where I spent most of my time. *Stars and Constellations* also has chapters on planets, comets, the Moon, and meteors. There is even a Hertzsprung-Russell diagram plotting stars' luminosity on a graph, which totally baffled my 8-year-old brain.

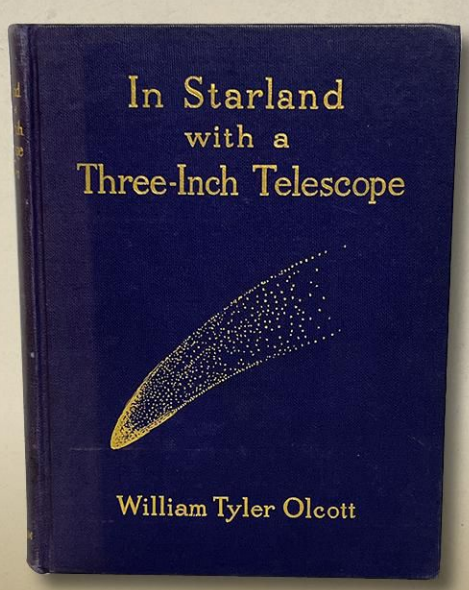
Not long after my mother gave me *Stars and Constellations*, I found a rather dog-eared copy of *Astronomy With an Opera-Glass* in the basement of our town's old Carnegie library. The library was opened in 1902, and this book looked like it had been there the whole time. Written by Garrett P. Serviss in 1888, it was a popular beginner's guide for many decades.

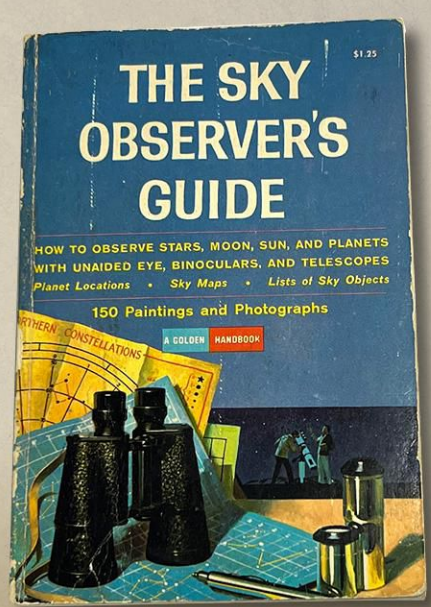
As a young amateur astronomer, I loved his colorful descriptions and flowery language, which brought sky observing to life. Serviss provided not only useful information, but also a sense of wonder and romance about the night sky. Almost forgotten today, Serviss became one of the most important popularizers of astronomy in the late 19th and early 20th centuries. Long out of print (although copies are easy to find), *Astronomy With an Opera-Glass* is still delightful to read and useful to beginners and seasoned observers alike.



For beginners

One of my favorite guidebooks measures a mere 3½ by 5¾ inches (9 by 15 centimeters). Despite its diminutive size, it made a huge impact on my

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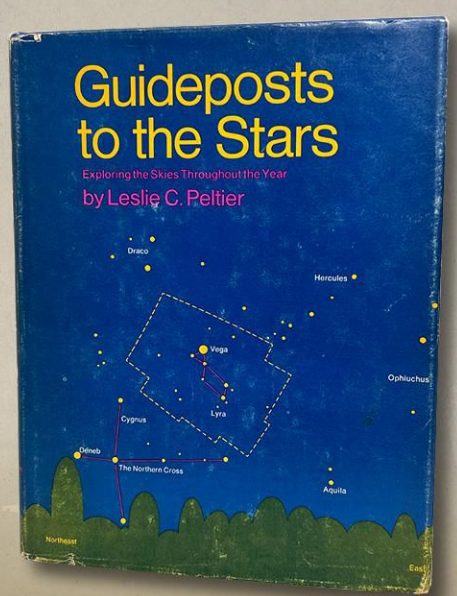


developing interest in astronomy. *The Observer's Book of Astronomy* by Patrick Moore was first published in 1962; my copy is from 1965. Moore wrote, "This book, however, is not written for the serious observer, but for the beginner." His book is reminiscent of the Golden Nature Guide. This little volume covers all the basics, from equipment to constellations and planets, the Moon, and even a bit about the then-nascent space race. It is filled with black-and-white images and written in Moore's straightforward style. It's easy to read, and it was an early addition to his long list of astronomy books.

Moore was, by definition, an amateur astronomer — self-taught and never appointed to a formal academic position. The introduction of this book tells the reader, "The main requirements [for an amateur astronomer] are enthusiasm and patience." This is good advice that has always stuck with me. In 1965, Moore published his guide *Naked-Eye Astronomy*. This month-by-month description of the night sky gives novice observers a "big picture of the yearly parade of stars and constellations."

William Olcott's *Field Book of the Skies* is a celestial guide that has been by my side for many years. An enthusiastic amateur and founder of the American Association of Variable Star Observers, Olcott first published *In Starland With a Three-Inch Telescope* in 1909 before gaining recognition with *Field Book of the Skies* in 1929.

The bulk of *Field Book* is dedicated to the constellations in an extremely accessible layout. Arranged by seasons, each entry begins with a summary of the constellation followed by a section for the unaided eye and field glass (binoculars). Each section has an accompanying star chart. It then concludes with a chart and description of objects for small telescopes. The book provides a wonderful step-by-step tour through the sky. *Field Book* was revised by the astronomers Robert and Margaret Mayall in 1954 but has since gone out of print. *The Sky Observer's Guide*, written by the Mayalls, was another of their contributions to the field.

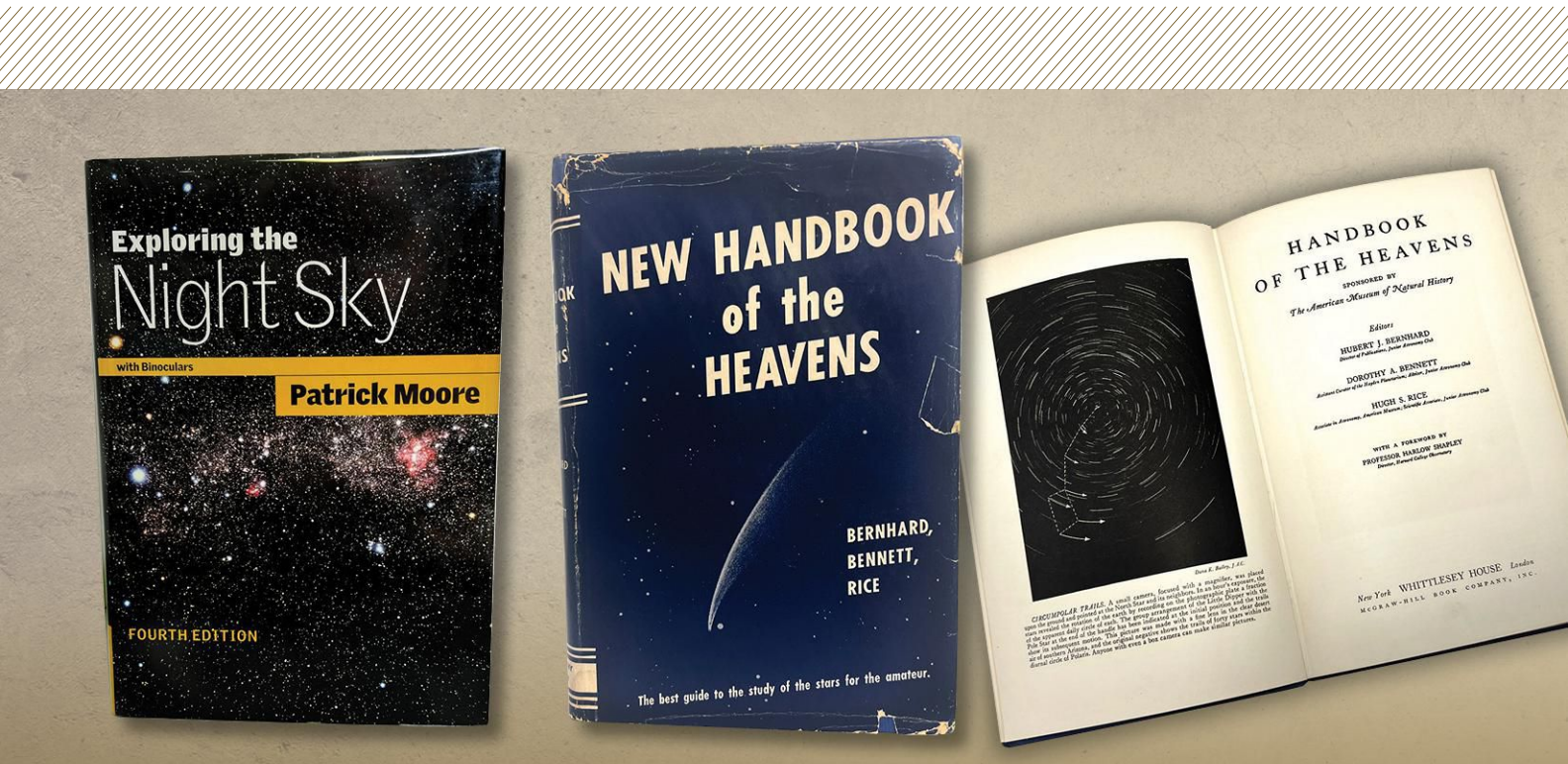
> When I got my first telescope, a small Tasco refractor, I turned it on the Moon. I used Dinsmore Alter's *Pictorial Guide to the Moon* to guide my initial observations.

Guideposts to the Stars by Leslie Peltier elevates the beginner's guide to the level of near poetry. I read Peltier's autobiography in the late '60s and was entranced by the story of this amateur astronomer. Peltier wrote his guide, released in 1972, assuming the reader is a "total stranger to the nighttime sky."

He begins the journey with 15 of the brightest stars, and guides the observer through the yearly panorama of constellations. Starting with spring and the star Vega (Alpha [α] Lyrae), Peltier weaves his own story into the descriptions of stars and constellations for a truly compelling experience. No matter how well I have come to know the sky, this is a book I still read for inspiration.

Leveling up

Beyond the basic guides to the night sky are those that take the novice into the world of more advanced observation. Patrick Moore wrote several useful guides, including *Exploring the Night Sky With Binoculars*. Published nearly a quarter-century



after *The Observer's Book of Astronomy*, it quickly became a go-to guide for scanning the sky at low magnification. I was a seasoned observer by the time I found this book, but it was still full of information I hadn't seen elsewhere.

Handbook of the Heavens was another well-thumbed book I found at my local library. First published in 1935, this guide was sponsored by the American Museum of Natural History in New York City and was a collaborative effort by both professional and amateur astronomers. *Handbook* is full of practical information on using telescopes to observe double stars, the Sun, the Moon, and the planets. I was especially drawn to the last chapter, called "Observational Scrapbook." It includes tidbits of information about meteorites, coordinate systems, and why the Moon can be seen north of the zenith in Florida. In the early 1940s, the book was revised and enlarged as the *New Handbook of the Heavens*. Information was added on variable stars, sky phenomena, and darkroom work. Sadly, the "Observational Scrapbook" chapter was deleted.

As I developed a more technical interest in observing, I turned to James Muirden's *The Amateur Astronomer's Handbook*. Muirden is a British amateur astronomer who has published books on telescope-making, observing with binoculars, and more. This 1968 book is a great introduction to telescopes and other equipment. The sections on observing the planets are still useful and relevant.

When I got my first telescope, a small Tasco refractor, I turned it on the Moon. I used Dinsmore Alter's *Pictorial Guide to the Moon* to guide my initial observations. Alter relates both history and physical aspects, making this more than just a guide to lunar features. I enjoyed his descriptions of the changing appearance of major lunar craters and what he terms "many peculiar aspects of the Moon's surface." Even though the explanations for those aspects have changed since the 1960s, this is still a wonderful guide to observing our nearest neighbor.

Beyond print

Not all beginner's guides to astronomy are in book form. Planispheres are simple star maps that can be set for any time and date throughout the year. The planisphere is a direct descendant of the ancient astrolabe, reduced to its simplest form. Being a collector, I have a stack of these devices. They are made of plastic, cardboard, and even wood. They also come in every size you might want.

I bought my first (and still my favorite) at the Adler Planetarium gift shop in Chicago. It is easy to use and best of all, the stars glow in the dark! One of the most popular of these devices was the *Barritt-Serviss Star and Planet Finder*, first printed in 1906.

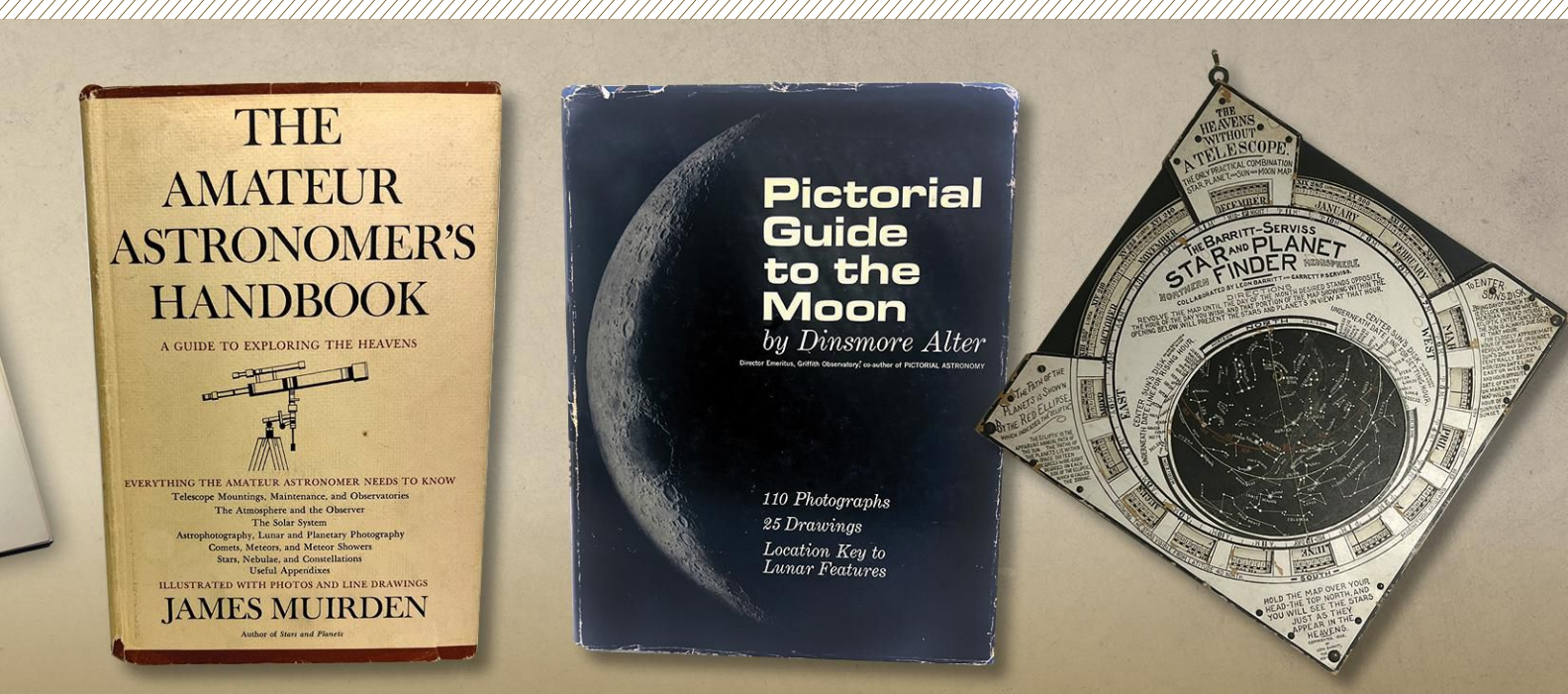
My most unusual guide was a vinyl LP of a sky lecture (one in a series) by Hubert J. Bernhard at Morrison Planetarium in San Francisco. It was the audio of a program touring the solar system. I ran across a magazine ad for the record, sent off the money, and received it a few weeks later. It seemed high-tech at the time. Recently, I found one on eBay to replace my original.

Obviously, I've dated myself with this list of guides that helped grow my interest in astronomy. My list could go on and would include *Astronomy* magazine, the Abrams Planetarium *Sky Calendar*, and even the *Old Farmer's Almanac*, which actually remains more practical than most people think.

We want to hear from you

There are many great beginner's guides I haven't mentioned. Which guides helped you along your path of discovery? Email our editorial team (astronomyeditorial@astronomy.com) and tell us and other readers what inspired you.

Raymond Shubinski *is a contributing editor of* Astronomy *who has observed and lectured about the sky for many, many, many years.*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Glorious globs

They're more than just spherical collections of stars.

The Milky Way's finest globular cluster is Omega Centauri. The author captured one hour of exposure March 8, 2024, through a 3-inch refractor from her dark-sky property in eastern Arizona.
MOLLY WAKELING

BY MOLLY WAKELING
Molly is an avid astrophotographer active in STEM outreach. She has a Ph.D. in nuclear engineering.

There is little I love more than gazing at a glittering globular cluster through a big, juicy Dob. The larger the mirror, the better! Each cluster looks a little different, and resolving individual stars is always a treat. Despite how easy they are to see, they are mysterious objects — and some of the oldest structures in the universe.

Globular clusters are dense collections of stars bound to each other by gravity. They can have anywhere from tens of thousands to millions of members.

Globs, as many amateurs refer to them, tend to lurk in the halos (spherical areas surrounding the cores) of galaxies, and you can find a bright one to observe in the early evening sky just about any time of the year. The prolific German-British astronomer William Herschel coined the term *globular cluster* in 1782. At that time, there were 34 known globular clusters, and Herschel went on to discover 36 more.

Our Milky Way now has roughly 150 known clusters, and a few from the neighboring Magellanic clouds are visible through amateur telescopes as well. Here are some of my favorites.

The most impressive globular cluster to witness is Omega Centauri — so named because it was long thought to be a star. Visible to the naked eye even under moderate light pollution, it was known in antiquity. Its true nature was finally understood in the 19th century with John Herschel's observations. I saw it for the first time from the Texas Star Party in Fort Davis. It is a Southern Hemisphere object with a declination of –47°, but from Fort Davis it just crests the hills to the south, rising to about 12° off the horizon, much to the delight of the northern astronomers who attend the event.

The most impressive globular cluster to witness is Omega Centauri.

Slightly larger on the sky than the Full Moon, it fills the view of even small telescopes with hundreds or thousands of stars, many that are easy to resolve. It's hard to take your eyes away! I could see it naked eye from La Serena, Chile, in the nights before the 2019 solar eclipse. My eye kept catching it whenever I was looking around the sky.

Omega Centauri lies a little less than 17,000 light-years away and is the largest known glob in the galaxy, home to an astonishing 10 million stars. It weighs in at 4 million solar masses, nearly the mass of our galaxy's central black hole, Sagittarius A*. Researchers believe it originated from the core of a dwarf galaxy that was swallowed by the Milky Way.

A frequent stop of mine at public stargazes and evenings with my friends is M13, known as the Hercules Cluster for lying within the boundaries of the constellation of the same name. At a distance of 26,000 light-years and with a population of hundreds of thousands of stars, it's a must-see on any summer night. Besides its beauty, my other favorite part is how easy it is to find. First look for the central part of Hercules, known as the Keystone. Spot the top two (eastern) or bottom two (western) stars of the square. M13 is almost in line between them, closer to Eta (η) than Zeta (ζ) Herculis. You can't miss it!

While there are many deep-sky objects that look better in a photograph than to the eye, globular clusters aren't one of them. Many globular clusters have apparent patterns in the stars that don't show up in images. M13 is a good example. Careful observing reveals a propeller shape on the southeast side, the result of three dust lanes that appear to converge at the same point.

There are plenty more globs worth observing that I haven't mentioned, but if you pan around the sky with binoculars or trawl through the Milky Way with a telescope, you're bound to spot some of these fuzzy balls. If you get a chance to look through a Dobsonian with a big aperture, definitely aim it at one of these dazzling objects. You won't be disappointed!

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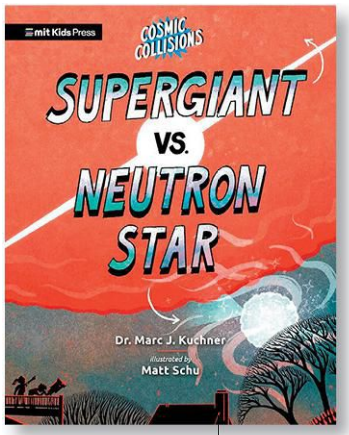

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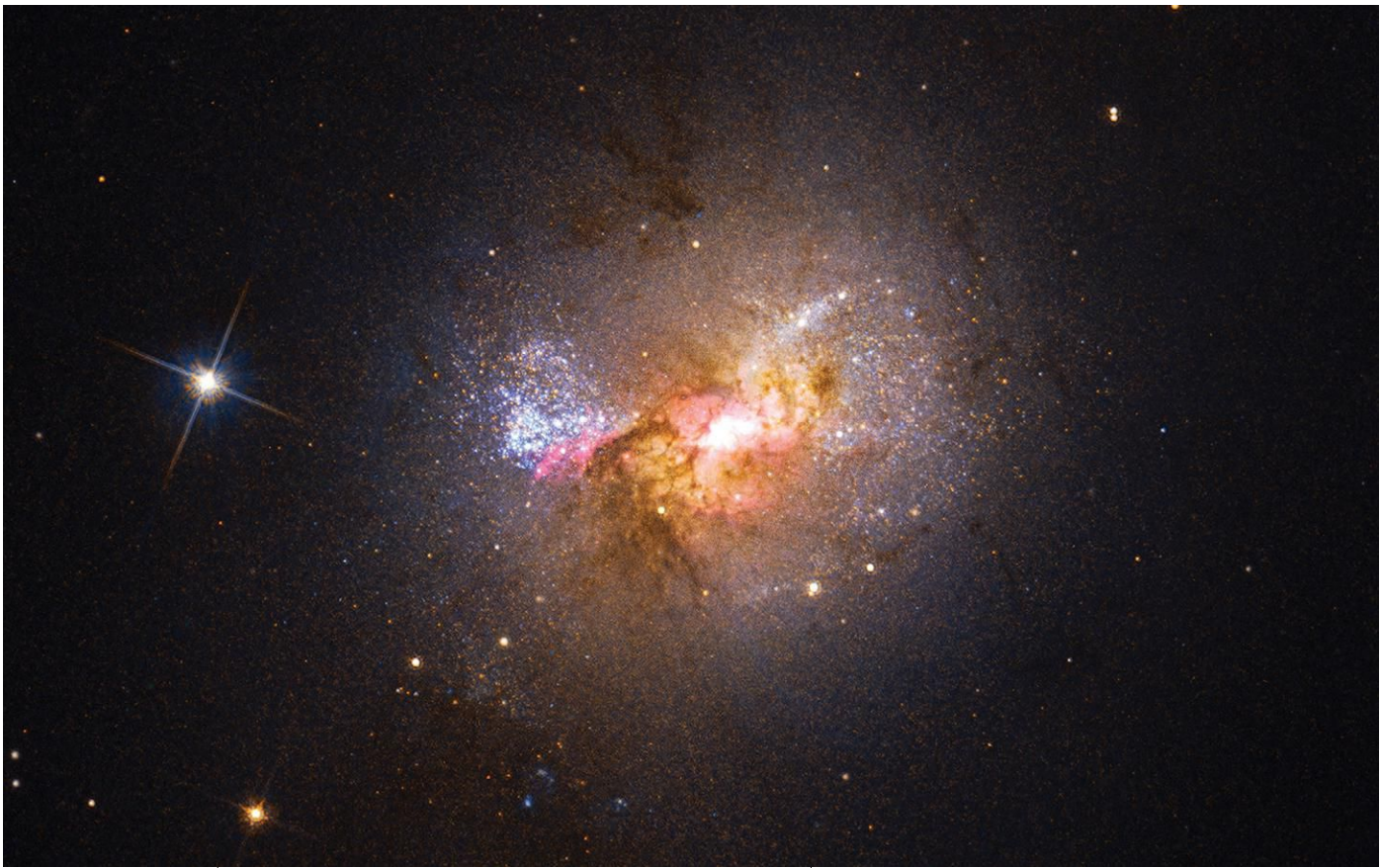


Outflows from the massive black hole at the bright center of dwarf galaxy Henize 2-10 are helping fuel star formation within the galaxy. NASA, ESA, ZACHARY SCHUTTE (XGI), AMY REINES (XGI); IMAGE PROCESSING: ALYSSA PAGAN (STSCI)

Dwarf galaxies

Q | DO DWARF GALAXIES HAVE A LARGE BLACK HOLE IN THE CENTER?

Duane Morse
Phoenix, Arizona

A | Nearly all massive galaxies are known to host central black holes. And dwarf galaxies can indeed also host central black holes, but whether all or only a fraction of them do remains an open question in astronomy.

Until recently, astronomers had identified active central black holes in only 0.5 percent of dwarf galaxies. However, a new study published in February revealed black holes in nearly 2 percent of the 115,000 dwarf galaxies observed. This fourfold jump suggests that a substantial number of black holes remain undetected in the low-mass galaxy regime. It further raises the possibility that even more black holes might be concealed within these galaxies, awaiting detection with improved observational techniques.

Identifying black holes in dwarf galaxies is far more challenging due to their faint nature and the difficulty in resolving them. This explains why astronomers have only recently begun to uncover them, and why we still do not know what fraction of dwarf galaxies actually host central black holes. With improved technology, we are steadily piecing together the answers to this question.

Dwarf galaxies harbor what are called intermediate-mass black holes (IMBHs), whose masses range from a hundred to a million times the mass of the Sun. These IMBHs are the missing link between stellar-mass black holes (less than 100 solar masses) that are formed from dying stars and the supermassive black holes (greater than a million solar masses) that dominate the centers of massive galaxies. So, the central black holes found in dwarf galaxies may hold the key to one of the biggest mysteries in astrophysics: how supermassive black holes, like the one at the center of our Milky Way, came to exist. Finding more of these elusive black holes and mapping their masses will help us uncover the origins of the very first black holes formed in the universe. Moreover, it will reveal how these objects interact with their host galaxies, and whether they can influence the

galaxy's growth and evolution over cosmic time.

Excitingly, astronomers have now detected IMBH candidates both in nearby dwarf galaxies using ground-based telescopes and in dwarf galaxies from the early universe, thanks to the James Webb Space Telescope.

Ragadeepika Pucha
Postdoctoral Researcher, Department of Physics & Astronomy, University of Utah, Salt Lake City

DWARF GALAXIES HARBOR INTERMEDIATE-MASS BLACK HOLES, WHOSE MASSES RANGE FROM A HUNDRED TO A MILLION TIMES THE MASS OF THE SUN.

Q | HOW IS THE TOTAL MASS OF THE UNIVERSE CALCULATED?

Bob Giddings
Green Bay, Wisconsin

A | Calculating the total mass of the universe is not simple, because most of the mass is invisible.

In a pie chart of the contents of the universe, only 5 percent is normal matter, atoms that make up all the planets, stars, and galaxies. About 95 percent is composed of two invisible, enigmatic entities. Dark matter represents 27 percent of the universe, and dark energy is dominant, about 68 percent of the universe. Setting aside dark energy, these ingredients are measured in different ways.

The normal matter is almost entirely hydrogen and helium, the two simplest elements. All the other elements in the periodic table are just 2 percent of the census. And even the normal matter is mostly dark: All the stars in a trillion galaxies comprise just 0.5 percent of the contents of the universe. The bulk of normal matter is either too cold or too hot to be easily seen. Various methods have been used to locate normal matter, but the most accurate estimate comes from measurements of the cosmic microwave background radiation, the afterglow of the Big Bang.

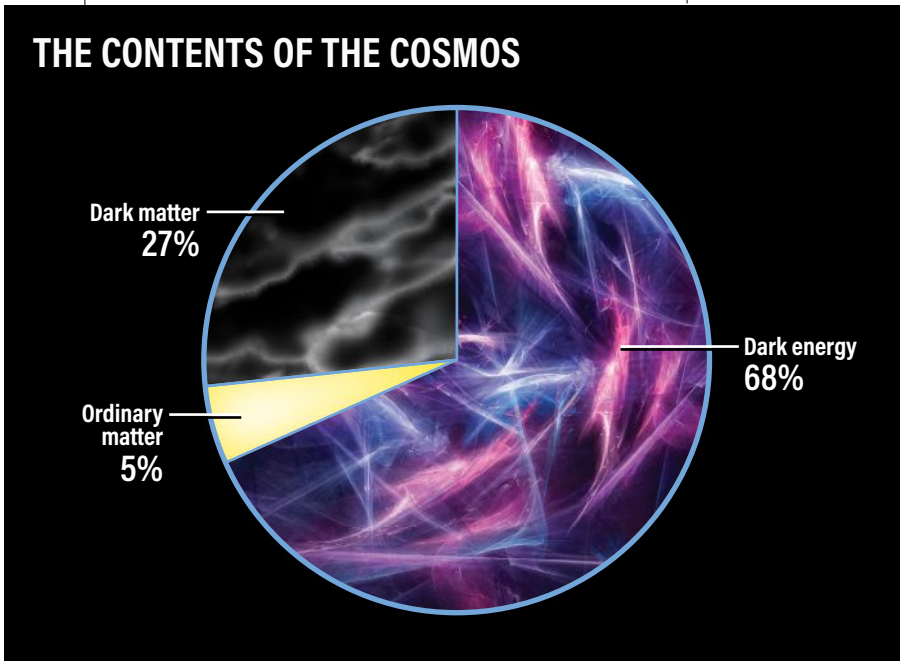
Dark matter outweighs normal matter by a factor of five or six. It was first noticed 50 years ago in the way spiral galaxies rotate. They rotate too quickly to be held together by all their stars, so there must be an extended halo of invisible mass surrounding the visible stars and gas. The way stars move in a galaxy can be used to measure the total mass, both visible and dark. Astronomers don't know what dark matter is, but suspect it is a new type of fundamental particle that doesn't interact with radiation.

An independent way of measuring mass in the universe is gravitational lensing. General relativity, our best theory of gravity, predicts that mass bends light. In gravitational lensing, light from a distant object is deflected by an intervening galaxy or cluster of galaxies. By studying lensing, astronomers can estimate the mass of the intervening objects, including dark matter. This method agrees with estimates based on the motions of stars and galaxies.

The mass of the entire universe can also be estimated by measuring how the expansion rate has changed since the Big Bang. Normal matter and dark matter have acted to decelerate cosmic expansion, while in the past few billion years, dark energy has dominated and is accelerating the expansion rate. Matching the changing expansion rate to a Big Bang model gives the mass of the universe. The mass is insufficient to overcome the effects of dark energy, so the universe will expand forever.

Estimating the mass of the universe leads to some spectacular numbers. There are about a trillion galaxies in the observable universe. All the normal matter in those galaxies comprises 10^{23} stars, 10^{53} kilograms, and 10^{80} atoms.

Chris Impey
Distinguished Professor of Astronomy, Department of Astronomy, University of Arizona, Tucson



This pie chart shows how little of the universe is composed of visible matter, while dark matter and dark energy make up some 95 percent of its contents. NASA'S GODDARD SPACE FLIGHT CENTER

The Moon sits high above the horizon as seen from the Arctic Ocean. PATRICK KELLEY/ U.S. COAST GUARD/USGS

SEND US YOUR QUESTIONS

Send your astronomy questions via email to **askastro @astronomy.com**. Be sure to tell us your full name and where you live. Unfortunately, we cannot answer all questions submitted.

Q IS THERE EVER A TIME THAT THE MOON DOES NOT SET OR RISE, JUST LIKE THE SUN DOES FROM CERTAIN LOCATIONS ON EARTH? CAN IT HAPPEN DURING ANY PHASE OF THE MOON?

Mark Narwa
Ottawa, Ontario

A Yes, there are places on Earth where the Moon does not appear above the horizon. There are also places where the Moon is circumpolar and doesn't set, at least for a period of time. To determine the locations where one would find the circumpolar Moon or see no Moon at all, we only need to know the Moon's declination. Declination measures a celestial object's angular distance relative to the celestial equator — the projection of Earth's equator onto the sky. One could regard declination as the celestial equivalent of latitude. The declination of an object directly on the celestial equator, such as the Sun during either equinox, equals zero. The declination of the north celestial pole is 90° and that of the south celestial pole is –90°.

A celestial object's declination determines its visibility region: where it's visible, not visible, and circumpolar. For instance, the Sun's declination on Nov. 12 is about –18°. Consequently, it will not be visible at any location north of 72° north, which is equal to 90 minus 18. Also, the Sun will be circumpolar at any location south of 72° south. On the winter (December) solstice, the Sun's declination is about –23.5°. At this time, the Sun will not be visible at any location north of 66.5° north (the Arctic circle) and will remain circumpolar at any location south of 66.5° south (the Antarctic circle). On the summer (June) solstice, when the Sun's declination is 23.5°, it will not be visible anywhere south of the Antarctic circle and will be circumpolar anywhere north of the Arctic circle. (Note: We are conveniently neglecting atmospheric refraction effects and the fact that the Sun is not merely a point in space.)

The same principle applies to the Moon or any other celestial object. Its declination determines its visibility region. For instance, if the Moon's declination is 10°, it won't be visible anywhere south of 80° south and will be circumpolar in any region north of 80° north. If you know the Moon's declination, you can subtract it from 90 to determine its region of circumpolarity and also where it won't rise above the horizon. Whereas the Sun is currently limited to a declination range between –23.5° and 23.5°, the Moon's range is between about 28.7° and –28.7°. Therefore, it will always rise and set between the latitudes of 61.3° north and 61.3° south. Those of us at midlatitudes will always see the Moon rise and set, just as we always see the Sun rise and set each day.

This variation is independent of phase. For instance, the summer solstice Full Moon has a much lower declination than the winter solstice Full Moon. So, the Full Moon that occurs around the first day of summer will be circumpolar in many regions south of the Antarctic circle and the winter solstice Full Moon will be circumpolar in many regions north of the Arctic circle. All that matters is the Moon's declination.

Edward Herrick-Gleason
Astronomy Educator, St. John's, Newfoundland and Labrador

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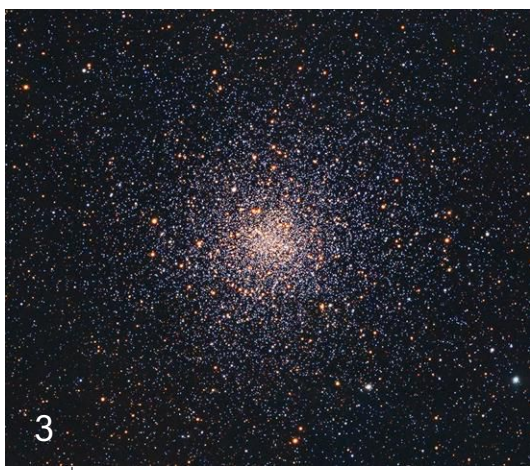
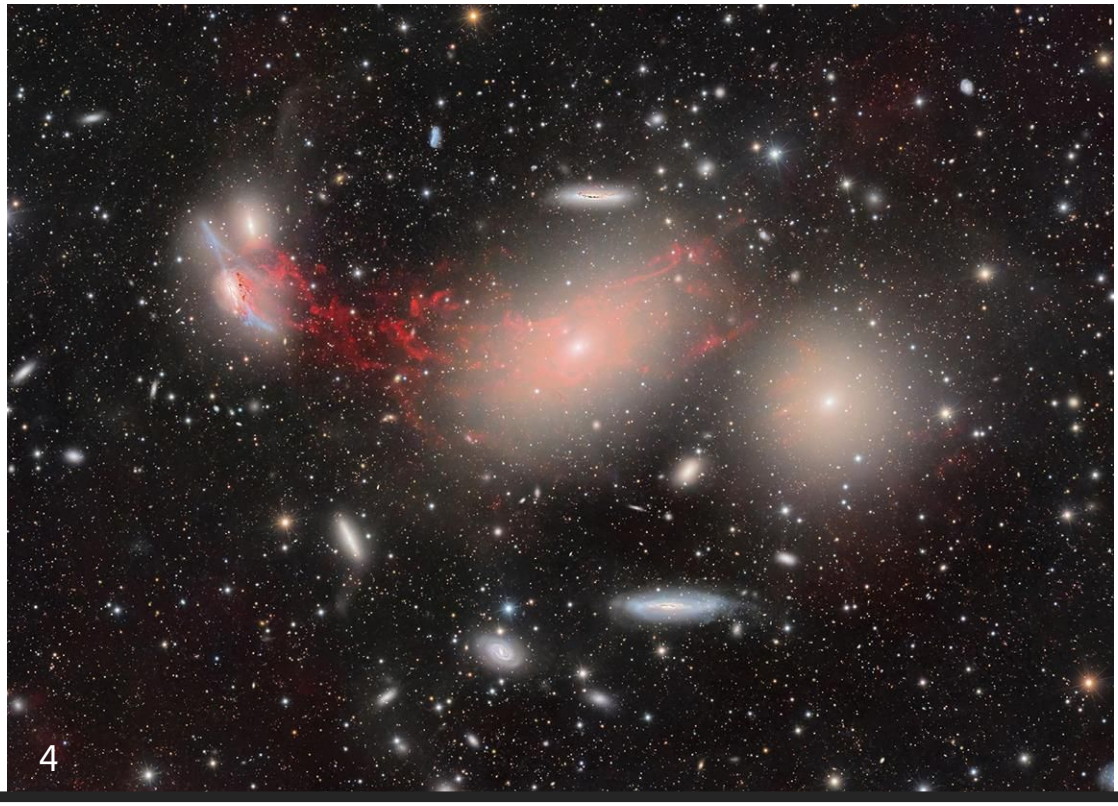


1. OVER THE RIVER
The Milky Way arches over the Cuckmere River in Sussex, U.K., in this blended panorama. The imager used a Canon DSLR and captured the sky panels with a 28mm f/1.4 lens and exposures of 52 seconds at ISO 800; the foreground panels were captured with a 13mm f/2.8 lens at exposures of 122 seconds at ISO 1600. ***• Marco Wong***

2. TO A BOIL
The Spaghetti Nebula (Sharpless 2–240) is the legacy of an exploded star, its energy having propelled debris into its surroundings. This image represents 567 hours of exposure in SHO filters from Bortle 8/9 skies taken over three winters with a 1.6-inch f/4.5 refractor, plus 1¼ hours of RGB data. Visible in the lower left is Mars, which visited the field in 2023. ***• Jeffrey Horne***

3. GLORIOUS RESOLUTION
Globular cluster M4 lies just west of Antares (Alpha [α] Scorpii). To a visual observer, a 6-inch scope reveals dozens of stars; this image comprising 2.6 hours of exposure resolves nearly the entire cluster. ***• Fernando Oliveira de Menezes***



4. A HIDDEN BRIDGE
Markarian's Chain is an alignment of galaxies in the Virgo Cluster, at least seven of which appear to move together. This deep image comprising 660 hours of data collected by 30 imagers reveals the bridge of ionized hydrogen that stretches from NGC 4438 to M86 — evidence of a previous gravitational interaction.
• Overall Photons: Francisco Javier Pérez Olvera, Manuel Alejandro Chavarría Silva, George William Hoffman, Kollar Istvan, Jonathan Schwab, Giovanni Lombardi, Fumio Saito, Francesco Morini, David Serquera, Lorenzo Lilli & Giampiero Lilli, Gianni Melis, Richard Mongold, Emanuele La Barbera, Michele Mazzola, Ashley Brown, Satoshi Iino, Jeff Ratino, Ulli Wittur Fee, Marco Martinelli, Roberto Volpini, Krzysztof Gaudy, Patrick Bisaillon, Darius Kopriva, Jacopo Fallai, Roberto Testi, Kyle Fisk, Andrea Iorio, Fernando Linsalata, Elisa Cuccu

5. MOONHATTANHENGE
A day-old crescent Moon is framed by the concrete jungle of New York City's 42nd Street in this shot captured at 9:10 P.M. on April 28. The photographer used a Canon mirrorless camera and 600mm lens, taking a 1/15-second exposure at f/6.3 and ISO 1600. ▪ ***David Gluchowski***

6. A SHOCKING MYSTERY
Abell 35 (Sharpless 2–313) in Hydra resembles a planetary nebula, surrounding a stellar binary that includes a white dwarf. However, the prominent bow shock suggests the binary system may simply be passing through an interstellar cloud, exciting it from within. This Hα/OIII/LRGB image comprises 35½ hours of exposure with a 24-inch scope. ▪ ***Vikas Chander***

7. YOU'RE GONNA NEED A BIGGER SCOPE
The Shark Nebula (LDN 1235) is a cloud of gas and dust that prowls the constellation Cepheus. Its "body" is dotted by young, blue stars, whose light reflects off of the dust. The imager captured this specimen after 16 hours of effort with a 4.2-inch scope in RGB filters. ▪ ***Adriano Anfuso***

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Please include the date and location of the image, your mailing address, and complete photo data: telescope, camera, filters, and exposures.

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END OF THE ROAD

Sun-like stars live long and uneventful lives. But after 10 billion years or so, such a star exhausts its nuclear fuel, swells into a red giant, and ejects its outer layers. The exposed core becomes a white dwarf that radiates ultraviolet light, which ionizes the expelled gases and causes them to glow, creating a planetary nebula. Kohoutek 4–55 is a stunning example. The nebula lies 4,600 light-years away in Cygnus, just 0.9° southeast of 1st-magnitude Deneb. Kohoutek 4–55 has an unusual, multilayered structure featuring an inner cloud of oxygen surrounded by a jagged ring of oxygen wrapped in a faint halo of nitrogen. This portrait not only captures the end of a star's life, but it also marks the final image captured by Hubble's Wide Field and Planetary Camera 2 in 2009. Scientists recently used state-of-the-art processing techniques to bring out greater detail than the original showed. ESA/HUBBLE & NASA, K. NOLL

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November 2025
A gas giant bonanza

As November begins, two of the solar system's rocky planets form a nice pair low in the western sky during twilight. They add a sparkle to our view of the constellation Scorpius the Scorpion as it sinks toward the horizon.

Innermost **Mercury** comes into view first. It shines at magnitude –0.1 and appears 8° directly below 1st-magnitude Antares on Nov. 1. The planet approaches within 4° of the Scorpion's brightest star during the month's second week.

Mercury looks even better when you view it through a telescope. As it moves closer to the Sun in advance of its Nov. 20 inferior conjunction, the inner world shows a beautiful crescent during moments of good seeing. The best viewing time comes around the 12th, when the planet's disk spans 9" and appears 22 percent lit.

Ruddy **Mars** joins Mercury in evening twilight during the first half of November. The two reach conjunction on the 12th, when Mercury slides 1.3° south (upper left) of Mars. The two make a fine sight along with Antares, and all three will fit in a single binocular field. Don't confuse the Red Planet with the red supergiant Antares. Magnitude 1.4 Mars lies below the star and appears a bit dimmer.

Turn a telescope on Mars and you're sure to be disappointed. It lies on the far side of the solar system from Earth and looks tiny, with an apparent diameter of just 4". Both Mars and Mercury disappear into the solar glare after midmonth.

Once darkness falls and Mercury and Mars have vanished, turn your attention to the north. There you'll find **Saturn** located about two-thirds of the way from the horizon to the zenith. The ringed planet shines at magnitude 0.8, easily the brightest object in the so-called water constellations that cover much of our spring evening sky. Saturn lies in the northeastern corner of Aquarius the Water-bearer, just across that constellation's border with Pisces the Fish.

A telescope transforms the planet from a bright point of light into a stunning world. Saturn's disk measures 19" across in mid-November while the ring system spans 42". You might have a hard time discerning the rings, however, because they tilt a minuscule 0.4° to our line of sight. Use the minimal glare from the rings to look for subtle details in the gas giant's atmosphere as well as several of the planet's moons.

You'll have to wait several hours for the next planet to appear, but it's worth the delay. **Jupiter** rises among the background stars of Gemini the Twins, to the south (upper right) of the constellation's two brightest stars, Castor and Pollux. At magnitude –2.4, the giant planet outshines all stars, including brilliant Sirius. Jupiter begins retrograde (westward) motion Nov. 11, heralding its upcoming opposition in January.

Wait until the planet climbs higher as dawn approaches before turning your telescope in its direction. With an equatorial diameter of 42" in mid-November, the gas giant's disk should show a wealth of detail under steady seeing conditions. The smallest instruments also reveal the planets four bright Galilean moons.

Although **Venus** is the brightest planet, it is essentially unobservable this month from mid-southern latitudes. The planet begins November 16° west of the Sun, but it stands just 2° above the eastern horizon 30 minutes before sunrise. The inner planet will return to view on March evenings.

The starry sky

If you look high in the north late on any November evening, you'll spot the sprawling constellation Cetus the Whale. This star pattern holds a single Messier object, the Squid Galaxy (M77), and it's worth exploring with a telescope.

French astronomer Charles Messier (1730–1817) compiled a list of non-stellar objects more than two centuries ago. His only interest was in finding comets — he discovered 13 independently — so he wanted to catalog those objects observers could mistake for comets. The Squid Galaxy became the 77th entry in his catalog.

Of course, no one recognized galaxies for what they were in Messier's time. Indeed, the great astronomer recorded the object as a "cluster of stars," even though he could not possibly have resolved any part of M77. He would have seen the object as a patch of light, as you will when you first set eyes on it. Look for M77 0.9° east-southeast of 4th-magnitude Delta (δ) Ceti. Once you have Delta in the middle of an eyepiece field, nudge the scope 20' south and wait a bit more than three minutes. M77 will then lie at the center of the field.

At 9th magnitude, the galaxy makes a fine target for relatively small scopes. A 7.5cm instrument is enough to spot it, but it appears better with greater aperture. The galaxy shows up easily because it has a concentrated central region.

M77 is a Seyfert galaxy — an active galaxy with a bright nucleus that emits strongly across a broad range of wavelengths. The radiation comes from an accretion disk surrounding a central supermassive black hole. It's the same process that powers quasars, but, unlike quasars, the galaxy itself shows up clearly.

Interestingly, M77 recently "migrated" across the celestial equator. In standard epoch 2000.0 coordinates, M77's center lies just 48" south of the celestial equator. But in the 25 years since, precession has carried the galaxy through the equator to the northern side. Its slowly changing declination current stands at 6' north.

STAR DOME

HOW TO USE THIS MAP

This map portrays the sky as seen near 30° south latitude. Located inside the border are the cardinal directions and their intermediate points. To find stars, hold the map overhead and orient it so one of the labels matches the direction you're facing. The stars above the map's horizon now match what's in the sky.

The all-sky map shows how the sky looks at:

11 P.M. November 1
10 P.M. November 15
9 P.M. November 30

Planets are shown at midmonth

MAP SYMBOLS

- Open cluster
- Globular cluster
- Diffuse nebula
- Planetary nebula
- Galaxy

STAR MAGNITUDES

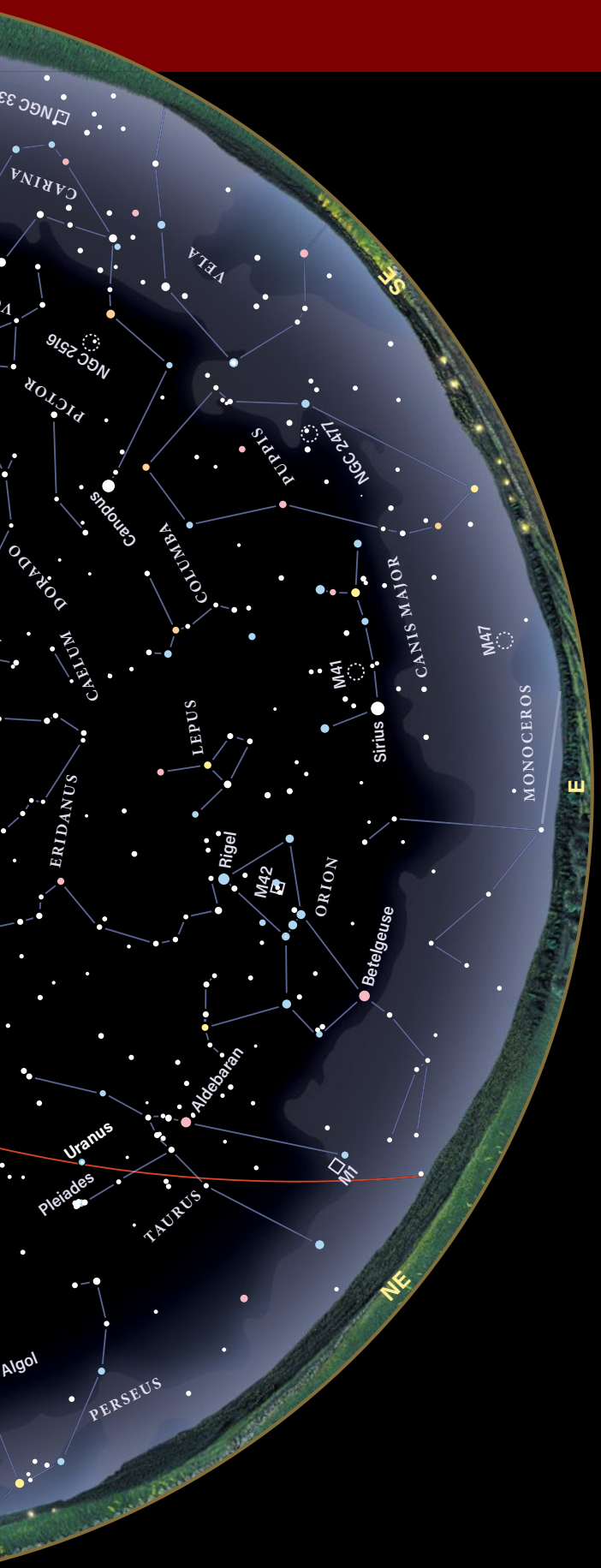
- Sirius
- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

STAR COLORS

A star's color depends on its surface temperature.

- The hottest stars shine blue
- Slightly cooler stars appear white
- Intermediate stars (like the Sun) glow yellow
- Lower-temperature stars appear orange
- The coolest stars glow red
- Fainter stars can't excite our eyes' color receptors, so they appear white unless you use optical aid to gather more light

BEGINNERS: WATCH A VIDEO ABOUT HOW TO READ A STAR CHART AT **www.Astronomy.com/starchart.**



NOVEMBER 2025

SUN.	MON.	TUES.	WED.	THURS.	FRI.	SAT.
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30						

Note: Moon phases in the calendar vary in size due to the distance from Earth and are shown at 0h Universal Time.

ILLUSTRATIONS BY *ASTRONOMY*: ROEN KELLY

CALENDAR OF EVENTS

1 Venus passes 4° north of Spica, 4h UT

2 The Moon passes 4° north of Saturn, 11h UT

The Moon passes 3° north of Neptune, 17h UT

5 Full Moon occurs at 13h19m UT

The Moon is at perigee (356,833 kilometers from Earth), 22h27m UT

6 The Moon passes 5° north of Uranus, 17h UT

9 Mercury is stationary, 23h UT

10 The Moon passes 4° north of Jupiter, 8h UT

Asteroid Papagena is at opposition, 15h UT

11 Jupiter is stationary, 20h UT

12 Last Quarter Moon occurs at 5h28m UT

Mercury passes 1.3° south of Mars, 19h UT

13 The Moon passes 1.0° north of Regulus, 0h UT

17 The Moon passes 1.2° south of Spica, 11h UT

Leonid meteor shower peaks

19 The Moon passes 6° south of Venus, 9h UT

20 The Moon is at apogee (406,691 kilometers from Earth), 2h48m UT

New Moon occurs at 6h47m UT

Mercury is in inferior conjunction, 9h UT

21 Uranus is at opposition, 12h UT

25 Mercury passes 1.1° north of Venus, 5h UT

The Moon passes 0.4° north of Pluto, 14h UT

26 Jupiter passes 7° south of Pollux, 19h UT

27 Dwarf planet Ceres is stationary, 23h UT

28 First Quarter Moon occurs at 6h59m UT

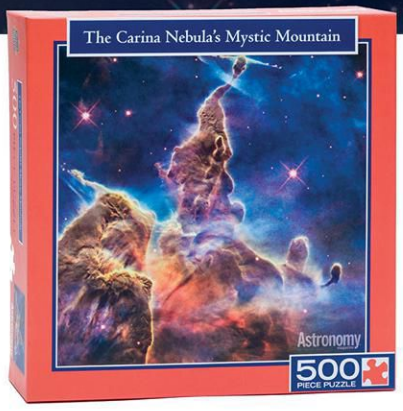
29 Saturn is stationary, 1h UT

Mercury is stationary, 15h UT

The Moon passes 4° north of Saturn, 19h UT

30 The Moon passes 3° north of Neptune, 2h UT

EXPLORE THE UNIVERSE



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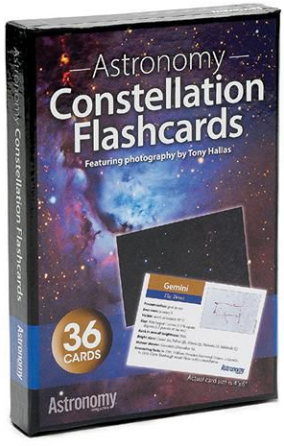

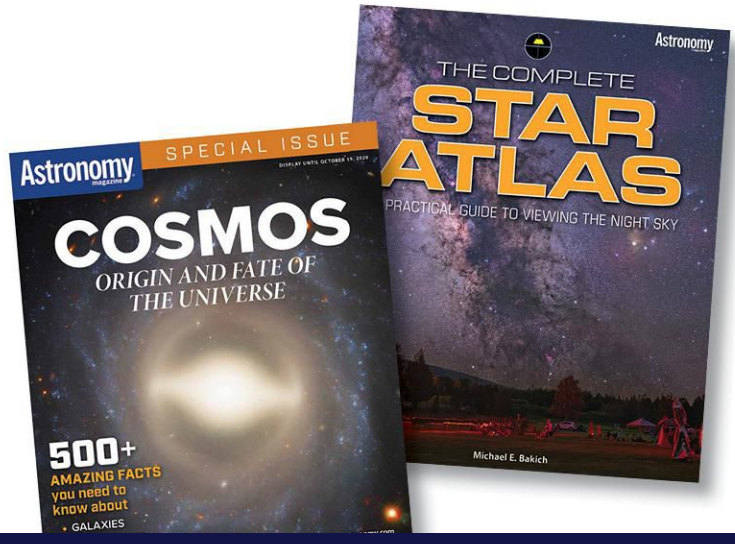

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